FLUKA studies of hadron-irradiated scintillating crystals for calorimetry at the High-Luminosity LHC

Milena Quittnat for the CMS Collaboration

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FLUKA studies of hadron-irradiated scintillating crystals for calorimetry at the High-Luminosity LHC

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1. Motivation
The Compact Muon Solenoid (CMS [1]) detector will be upgraded for the High-Luminosity LHC (HL-LHC). The HL-LHC is scheduled for 2022 and will provide a five times higher instantaneous luminosity ($\mathcal{L} = 5 \cdot 10^{34}$ cm$^{-2}$ s$^{-1}$) than the LHC. Calorimetry at the HL-LHC will be performed in a harsh radiation environment with high hadron fluences, where typical doses in the forward region will be around 30 Gy/h at $|\eta| = 2.6$. The current forward electromagnetic calorimeter (ECAL endcaps, EE) is designed for LHC running with an integrated luminosity of 500 fb$^{-1}$. In the forward region, this calorimeter consists of $2 \times 61200$ Lead Tungstate (PbWO$_4$) crystals and covers a region of $1.48 < |\eta| < 3.0$. The PbWO$_4$ crystals show a cumulative hadron-induced damage, which degrades the energy resolution [3] and makes a replacement of the EE for the HL-LHC desirable. One option for an upgraded forward ECAL would be a sampling calorimeter with alternating layers of absorber (tungsten), and active plates of a heavy inorganic scintillator. Suitable candidates are cerium fluoride (CeF$_3$), cerium-doped lutetium orthosilicate (Ce$_{2x}$(Lu$_{1-x}$Y$_y$)$_2$SiO$_5$ - LYSO) and cerium-doped yttrium orthosilicate (Ce$_{2x}$Y$_{2(1-x)}$SiO$_5$ - YSO). These sampling calorimeter designs have to be studied in terms or radiation properties under HL-LHC conditions, using the Monte Carlo simulation program FLUKA ([6], [7]) which is optimized for such studies.

2. Comparison of FLUKA simulation to proton irradiated crystals
One goal of the following FLUKA radio-activation simulation is to validate the FLUKA description of the respective materials with measurements. The results of this study are
Figure 1. Measurements of induced ambient-dose equivalent rate $\dot{H}^\ast(10)_{\text{ind}}$ at 5.7 cm from the side of the crystals as a function of time after irradiation, compared to FLUKA simulations for a fluence $\Phi_p = 10^{13} \text{p/cm}^2$. The measurements are affected by a relative scale uncertainty of 7% due to the precision of fluence determination [4].

described in detail in [4]. A LYSO sample with the dimension of $25 \times 25 \times 100 \text{mm}^3$, corresponding to $8.8X_0$ in length, was irradiated with 24 GeV/c protons up to a fluence of $\Phi_p = (8.85 \pm 0.62) \times 10^{12} \text{cm}^{-2}$ at the CERN PS T7 beam line. Since the fluence in this test has been delivered to the samples over few hours, the rate values measured here are not representative for what would be observed in situ [4]. However, the comparison between different crystal types is crucial to anticipate the expected exposure. The induced ambient-dose equivalent rate (“dose”) $\dot{H}^\ast(10)_{\text{ind}}$ has been measured at 5.7 cm distance from the middle of the LYSO sample at various times after irradiation. The measurements are compared with results from a FLUKA simulation (version 2011.2b.3), after rescaling to $\Phi_p = 10^{13} \text{p/cm}^2$. A very good agreement is observed in Fig. 1, between FLUKA simulations and measurements, over one year and over two orders of magnitude in dose, with the simulation results falling slightly on the low side. Uncertainties in the comparison can arise from the limited knowledge of Lutetium cross-sections in FLUKA, and from non-uniformities of the beam intensity during irradiation combined with the self-shielding of the crystal. The comparison benchmarks the reliability and predictive power of FLUKA for such LYSO crystals.

In a second step, FLUKA simulations have been performed to compare the expected remnant radioactivity among crystals of similar dimensions in terms of radiation lengths ($26X_0$), while keeping the granularity the same ($24 \times 24 \text{mm}^2$). The description of CeF$_3$, based on [5], was added to the comparison. The simulation results for PbWO$_4$ are compared to existing measurements [3]. Accordingly, the crystals were assumed to be proton-irradiated with a 20 GeV/c squared beam profile for an integrated fluence of $\Phi_p = 10^{13} \text{p/cm}^2$. The $\dot{H}^\ast(10)_{\text{ind}}$ for each crystal was recorded as described in [4] and is depicted in Fig. 2. The FLUKA simulations for LYSO show a remnant dose similar to the one of PbWO$_4$, with the LYSO results being roughly a factor two above the PbWO$_4$ results. This is an indication that LYSO might become slightly more radioactive than PbWO$_4$ in a $26X_0$ deep calorimeter. As the transverse dimensions are kept the same, CeF$_3$ has effectively a smaller density. This smaller amount of material leads to a $\dot{H}^\ast(10)_{\text{ind}}$ which is a factor two lower. In conclusion, the remnant dose rate for LYSO and CeF$_3$ is expected to be similar to PbWO$_4$ in a $26X_0$ transversely extended calorimeter.

3. FLUKA studies for a forward ECAL for CMS at the HL-LHC
This section studies the behavior of an electromagnetic calorimeter in the forward region of CMS at the HL-LHC. The simplified FLUKA geometry is optimized to study the overall behavior of the sampling calorimeter with respect to radiation properties.

3.1. Implementation of CMS ECAL in FLUKA simulation
The implementation of a sampling calorimeter in the EE is based on the available baseline FLUKA geometry version 1.0.0.0, corresponding to the situation prior to the long shutdown 1
Figure 2. Induced ambient dose equivalent rate $H^*(10)_{\text{ind}}$ at distance 5.7 cm from the side of the crystal as a function of time calculated with FLUKA for a LYSO and CeF$_3$ crystal exposed to a fluence $\Phi_p = 10^{13}$ p/cm$^2$ of 20 GeV/c protons. These simulations are compared to data and simulations for PbWO$_4$ from [3] for the same irradiation conditions (all crystals 26 $X_0$ long). The uncertainties are discussed in the text. Based on Fig. 8 in [4] with updated results from [5].

Figure 3. CMS geometry and sampling calorimeter in EE in FLUKA (CMS Beam Radiation, Instrumentation and Luminosity Project, BRIL, version 1.0.1-3).

Table 1. Dimensions of the sampling calorimeter options in terms of activation.

<table>
<thead>
<tr>
<th>Calorimeter</th>
<th>$L_{\text{calo}}$ [cm]</th>
<th>$L_{\text{abs}}$ layer [cm]</th>
<th>$L_{\text{scint}}$ layer [cm]</th>
<th>$X_{\text{eff}}$ [cm]</th>
<th>$\rho$ [g/cm$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>YSO/W</td>
<td>22.0</td>
<td>0.5</td>
<td>1.00</td>
<td>0.880</td>
<td>4.5</td>
</tr>
<tr>
<td>CeF3/W</td>
<td>15.4</td>
<td>0.5</td>
<td>0.56</td>
<td>0.616</td>
<td>6.2</td>
</tr>
<tr>
<td>LYSO/W</td>
<td>12.7</td>
<td>0.5</td>
<td>0.38</td>
<td>0.508</td>
<td>7.1</td>
</tr>
</tbody>
</table>

(LS1), that lasted between February 2013 until January 2015. Only the region of the current PbWO$_4$ crystals in the EE is modified (320 cm – 342 cm in z). The chosen sampling calorimeter starts with a scintillator layer to be sensitive to effects of the CMS environment. It consists of 15 scintillator and 14 tungsten layers. The 25 $X_0$ depth of the current PbWO$_4$ crystals in the EE is kept. For comparison, the dimensions in terms of radiation lengths are chosen to be the same for all options considered: 25 $X_0$ are split into 5 $X_0$ for the scintillator and 20 $X_0$ for the absorber. If the total length is smaller than 22 cm, the rest of the volume is filled with a region of low mass density, reflecting electronics and cooling devices. The dimensions of the calorimeter options are listed in table 1.
3.2. Particle fluence in the sampling calorimeter at the end of HL-LHC

The primary proton-proton collisions with an energy of 7 TeV per beam were simulated with the DPMJetIII event generator and normalized to an inelastic collision cross section of 80 mb, using FLUKA version 2011.2b.5. Precise thresholds for the particle transport were applied. The transport and production thresholds were set to 100 keV for electrons and positrons, and to 50 keV for photons in the EE. Every other particle was transported down to 100 keV and the low energy neutron transport down to thermal energies ($10^{-5}$ eV) was included. The electron and positron fluence in the EE for 3000 fb$^{-1}$ as a function of depth, expressed in $X_0$, is depicted in Fig. 4. The fluence is averaged over a region of $48 \text{ cm} < R < 109 \text{ cm}$, corresponding to $1.8 < \eta < 2.6$ for $z = 320 \text{ cm}$. The z-coordinate was converted to $X_0$ by scaling with the effective radiation length $X_0^{\text{eff}}$, using a bin size of 10% of $X_0^{\text{eff}}$. For all options the average fluence is similar and comparable to the values of the PbWO$_4$ crystals. Most of the electromagnetically interacting particles in a minimum bias environment have an energy of a few MeV up to 1 GeV. The fluence reflects the development of the electromagnetic shower of such particles. The maximum electromagnetic particle flux develops in the first 7 $X_0$, particularly in the second scintillator layer. The effect due to the difference in density of the scintillator materials is clearly visible up to 11 $X_0$. In conclusion, the predicted electron-positron fluence will be comparable to the one of the current PbWO$_4$ crystals after 3000 fb$^{-1}$. Further studies show that the magnitude and overall shape of other particle fluences are also similar among the different sampling calorimeter options.

3.3. Absorbed dose in the sampling calorimeter at the end of HL-LHC running

The absorbed dose is the deposited energy per unit mass of the medium. Fig. 5 shows the dose absorbed in the EE for an integrated luminosity of 3000 fb$^{-1}$ as a function of the radiation length $X_0$ in the same region as above. Comparing the CeF$_3$ and YSO sampling calorimeters with the PbWO$_4$ calorimeter, the absorbed dose is overall comparable. The LYSO layers however show a significantly higher absorbed dose. This can be explained by the high thermal neutron capture cross section of $^{175}$Lutetium ($\sigma_{\text{th,n.}} = 23.1 \text{ barn}$ [2]). In Fig. 6 an estimation of the maximum neutron fluence energy spectrum, which occurs in the second scintillator layer at $2.2 < \eta < 2.6$ (see Fig. 4) after 3000 fb$^{-1}$ is depicted. In the region of low energy neutrons, the number and width of the bins is given by the thermal neutron cross section library in FLUKA. Thermal neutrons carry an energy up to a few eV, followed by a resolved resonance region. This region shows different resonances for each option due to the different elements in the materials. Because of the high thermal neutron capture cross section of Lutetium, the LYSO/W option shows a
significantly lower fluence for thermal neutrons. This explains the higher absorbed dose in the LYSO layers in Fig. 5. Further FLUKA simulations show that the thermal neutron fluence in the low density regions adjacent to both sides of the sampling calorimeter is higher than the one in the scintillator materials. The enhancement is likely also due to the polyethylene layers at both sides, which moderate neutrons down to thermal energies, but do not absorb them. Due to the high $\sigma_{th,n}$ of Lutetium, the absorbed dose rate in LYSO increases significantly at both ends of the calorimeter and in the scintillator layers. A thin absorber layer made out of boron polyethylene at both ends is advisable to moderate neutrons and absorb the thermal ones.

3.4. Study of a potentially prohibitive background due to decaying isotopes

The energy emitted by decaying isotopes might lead to a prohibitive background to the main electromagnetic signal. The LYSO/W calorimeter shows the highest dose values and is thus surveyed in a conservative scenario. Fig. 7 compares the absorbed dose rate ($\dot{D}$) during HL-LHC running ($1.44 \times 10^{13}$ pp-int./h) with the $\dot{D}$ by decaying particles at the irradiation stop after 2475 fb$^{-1}$. The irradiation schedule follows the official recommendations for a radioactivation simulation from LS3 until LS5. For the activation study, coalescence and evaporation of heavy fragments were enabled. $\dot{D}$ is visualized for two regions in R: 48 cm - 71 cm and 109 cm - 135 cm, corresponding to $\eta = 1.6$ - 1.8 and 2.2 - 2.6 at $z = 320$ cm. The inelastic cross section of the prompt electromagnetic shower is normalized to running conditions whereas the decay products are normalized to 100 mb, a conservative limit adopted for activation studies.
Absorbed dose rate due to the prompt electromagnetic shower and the decay products for an LYSO/W sampling calorimeter using FLUKA. The absorbed dose rate is projected to the calorimeter length in z, from 320 cm - 332.7 cm.

In Fig. 7, the dose rate $\tilde{D}$ in the higher $\eta$–region is on average one order of magnitude higher than the one of the lower $\eta$–region. In comparison, the dose rate of the decay products is at a constant 1 % level of the prompt particles. This offset of deposited energy by decaying isotopes is still at a manageable level for HL-LHC running. The overall activity of the created residual nuclei after $2475 \, \text{fb}^{-1}$ in the first scintillator layer at $2.2 < \eta < 2.6$ is $A = (4.53 \pm 0.07) \times 10^{10} \, \text{Bq}$. A percentage of 96% of this activity comes from residual nuclei created by low energy neutrons. Furthermore, the dose rate of the decay products is dominated by short lived radio nuclides. The deposited energy by the decaying isotopes after 10 h is one third of the one after $2475 \, \text{fb}^{-1}$. Responsible for this slight build-up is mainly the long lived isotope $^{177}$Lutetium with an activity of $A = (1.91 \pm 0.03) \times 10^{10} \, \text{Bq}$ after $2475 \, \text{fb}^{-1}$ and a half life of $\tau = 6.64 \, \text{d}$.

3.5. Conclusions
A possible forward electromagnetic sampling calorimeter for the CMS experiment at HL-LHC was studied in terms of radiation exposure. The dedicated FLUKA study shows that the average particle fluence and the absorbed dose are similar for all options considered. As the ionizing dose in a LYSO-tungsten sampling calorimeter increases significantly towards both ends, a thin boron-polyethylene layer at both ends would be advisable. The deposited energy by decaying isotopes is at a constant 1 % level of the prompt electromagnetic shower and is dominated by short-lived radioisotopes. All three designs, using tungsten as an absorber and CeF$_3$, LYSO or YSO as the sensitive material are suitable candidates for a future sampling calorimeter at the HL-LHC in terms of activation levels.

References