Upgrade of the LHCb ECAL monitoring system

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Abstract. The LHCb ECAL is a shashlik calorimeter of 6016 cells, covering 7.68×6.24 m² area. To monitor the readout chain of each ECAL cell, the LHCb ECAL is equipped with a LED based monitoring system. During the LHC Run I (2009-2012) it was found that the precision of the monitoring suffers from the radiation degradation of transparency of polystyrene clear fibers used to transport the LED light to the ECAL photomultipliers. In order to improve the performance of the monitoring system, and especially in view of significant increase of LHCb working luminosity foreseen after 2018, the present plastic fibers have been replaced by radiation hard quartz fibers. The performance of the old LHCb ECAL monitoring system during LHC Run I and the design of the upgraded system are discussed here.

1. Introduction

The LHCb ECAL design is described in [1]. It is a shashlik calorimeter of 25 X₀ thickness, covering 7.68×6.24 m² area. It is subdivided into 6016 cells. The light produced in each cell is read out by a PMT; the PMT anode signal is digitized by an ADC.

To monitor the functionality of the readout chain of each ECAL cell and the stability of its characteristics, the LHCb ECAL is equipped with the LED based monitoring system. The value of average photomultiplier response to light flashes of fixed intensity is used to follow up the behavior of each readout channel, mostly determined by the stability of the PMT gain. The details of the monitoring system design can be found in [1].

The monitoring system is organized such that each LED illuminates a group of 9 or 16 ECAL cells. The 6016 cells of LHCb ECAL are illuminated by 456 LEDs. Red LEDs of type Ligitek LUR3333H, with emission peak at 630 nm, are used. The stability of LED flash magnitude is monitored by PIN photodiodes (HAMAMATSU S1223-01). Each PIN photodiode serves a group of 2 or 4 LEDs; the LED firing sequence ensures that two LEDs within same group never flash simultaneously.

The LEDs, PIN photodiodes and corresponding electronic boards are installed below and above the calorimeter, outside the high radiation area. The light is distributed to each PMT by means of 2–8 m long light guide made of polystyrene-based KURARAY Clear-PCM fiber of 1 mm diameter.

The LHCb ECAL monitoring system comprises 6016 light guides grouped into 456 bundles, 456 LEDs and 124 PIN photodiodes. The total length of clear fibers is 28.6 km.

2. Performance and use of the ECAL monitoring system

The ECAL monitoring system played an important role at the commissioning and initial calibration phase [2]. During the LHCb data taking, it is also kept continuously running. The
Evidence of clear fiber degradation in LHCb ECAL: a the ratio of LED amplitudes on June 06, 2012 to those on May 02, 2012, for each ECAL cell; b the evolution of average LED signal for the two upper rectangular areas shown in a; c the evolution of average LED signal for the two lower areas.

LED pulses are sent to PMTs at approximately 50 Hz rate, at so-called empty LHC bunch crossings, in order to not interfere with physics events. The LED data, in form of amplitude spectra for every calorimeter cell, are stored to disk every 10–15 minutes.

As ECAL data participate in the LHCb L0 trigger decision [1], any instability of PMT gains affects the L0 rate. The gain of PMTs in the ECAL centre, in particular, degrades because of dynode system ageing at high particle rate [3]. The LED data could be used for monitoring the PMT gains and their adjustment when necessary. In order to keep the gain stable within 1-2%, the gain adjustments should be performed every several days.

However it was found that the precision of PMT gain monitoring with LED system is affected by radiation damage of the long light guides transporting LED light to calorimeter cells. It is illustrated in Figure 1. The particle rate in the four symmetrically placed areas, and therefore the average PMT gain degradation rate, is expected to be the same; however we see a 14% difference between upper and lower areas. It can be attributed to the difference in the transparency loss of the light guides, which is determined by their layout. For all these areas the LEDs are installed under ECAL. Therefore for the two upper areas the light guides are significantly longer than for the lower ones (6–8 m vs 2–4 m), and pass through the $y = 0$ plane, where the particle rate (dose rate) is significantly higher than in the selected areas themselves. According to the simulation studies [4] and recent measurements of the radiation doses in LHCb, the 14% difference shown in Figure 1 corresponds to a dose of $\sim$10 krad accumulated mainly by $\sim$1 m long parts of light guides at $-0.5 < y < 0.5$ m.

As the required ECAL calibration precision is $\sim$1%, the LED monitoring data were not used for PMT gain following in LHCb Run I.

In order to enable the precise PMT gain following in ECAL, it was decided to replace in 2014 the present light guides to new ones, made of radiation tolerant quartz fibers.

We are planning to use the following ECAL calibration procedure. In order to stabilize the PMT gains, LED-based HV corrections will be performed every few days$^1$. However the LED

$^1$ The method of stabilizing raw occupancies in the ECAL cells for minimum bias events, which is now under development, can also be used for the HV corrections.
The irradiation setup.

Figure 2. The irradiation setup.

The radiation system monitors only PMT gain variations, and does not follow the degradation of light yield of ECAL cells arising from radiation damage of scintillator and WLS fibers of shashlik structure. The radiation degradation of ECAL cells proceeds slower than PMT gain variations; to take the former into account, precise offline calibration based on the π0 peak position [5] will be performed every 2–3 month. The results of such calibration will be used to calculate the starting values of PMT HV for the next period.

The radiation degradation of the light guide transparency is determined, to a first approximation, by the dose integral over the fiber length. For LHC Run II, when LHCb will run at the luminosity of $4 \cdot 10^{32} \text{cm}^{-2}\text{s}^{-1}$, it does not exceed 100 krad·m per year (2 fb$^{-1}$).

After 2018, LHCb will be upgraded for work at 5 times higher luminosity, $2 \cdot 10^{33} \text{cm}^{-2}\text{s}^{-1}$ [6]. However, the dose rate at the ECAL front face, where the light guides are placed, will increase by less than factor of 2, because the Preshower detector in front of ECAL will be removed. The precise calibrations at high luminosity running will be performed more frequently, according to the increase of the degradation rate of the ECAL light yield.

In any of these two modes of operation, the dose integral over the length of any light guide accumulated during a period between two precise calibrations will not exceed 100 krad·m. Therefore the radiation damage of light guides will not significantly affect the calibration if the degradation of transparency of the quartz fiber is less than 1% per metre for 100 krad. This can be considered as a requirement for the radiation tolerance of quartz fibers.

3. Selection of components

The radiation damage of quartz fibers for visible light was extensively studied for CMS HF [7, 8, 9]. It was found that the best radiation hardness for visible light can be obtained with quartz fibers with pure silica – high OH$^-$ core and F-doped silica cladding. Their radiation hardness is at least two order of magnitude higher than that of Clear-PSM fibers.

The radiation loss of transparency of pure silica – high OH$^-$ quartz fibers depends on the wavelength (see e.g. Figure 1 in [8]). Within the range of PMT photocathode sensitivity, the minimum radiation damage is observed between 400 and 500 nm. Obviously, the red LEDs of present monitoring system have to be replaced to blue ones. We have chosen Multicomp OVL-5523 with emission spectrum peaking at 460 nm. The choice criteria were good timing characteristics and highest signal amplitude obtained with existing ECAL LED drivers and PMTs, compared to other available LED types.

The LHCb ECAL HV setting scheme is such that the PMT gain is roughly proportional to the distance between the cell and the beam axis [1]. The PMTs in the very central cells work therefore at rather low gains, order of $10^3$. In order to obtain LED signal in the middle of ADC range, the LED flash should produce $1-2 \cdot 10^5$ photoelectrons. The maximum amount of light
delivered to PMT is determined by the fiber diameter. With the chosen LED type and existing LED driver capabilities, the optimal fiber core diameter was found to be 200 μm.

The 200 μm diameter quartz fibers with pure silica / high OH⁻ core and F-doped silica cladding are available from several producers. All of them are expected to satisfy the requirements of the ECAL monitoring system. Our choice, made on the lowest price basis, was FVP200220240 fiber from Polymicro Technologies, Inc., USA.

4. Irradiation studies
As it was already mentioned above, a large array of data on radiation degradation of quartz fibers is available. Most of them are taken for multi-Mrad doses and sizeable transparency losses. Because of non-linear dependence of the degradation on dose, and reported dependence on dose rate, the extrapolation to relatively low doses and few percent degradation is not obvious. For this reason, it was decided to perform dedicated measurements.

The test was performed in June 2013 at the cyclotron of UCL (Louvain-la-Neuve, Belgium). Two types of fiber were tested: FVP200220240 (Polymicro) and MIS-166 (Fryazino, Russia), both with 200 μm diameter core. Two 5 m long samples wound on a 6 cm diameter spool were irradiated with a 62 MeV protons. The important feature of this facility is a broad beam with rather uniform profile: ±10% variations within 8 cm diameter core. The beam flux was set to \(2 \times 10^8\) p/cm²/s, which produced the dose rate in quartz of \(\approx 28\) rad/s.

The transparency of the two samples was continuously monitored during the irradiation and 12 h afterwards. The experimental setup is shown in Figure 2. The samples were connected to the light source and to the measurement equipment placed in the control room via 8m long light guides made of FVP200220240 fiber. To monitor possible degradation of these light guides, a dedicated control fibers of the same kind were used (see Figure 2). We studied only the spectrum

\[\text{Figure 3. Results of the irradiation test of quartz fibers: relative transparency degradation per 1 m of fiber during the test. At the insert: dose dependency of the long-term part of the transparency degradation, measured after 20 minutes annealing. Red stars: fiber FVP200220240; black triangles: MIS-166.}\]
range of interest: the blue LED Multicomp OVL-5523 selected for ECAL was used as a light source. The output light was measured by PIN photodiodes HAMAMATSU S1223-01.

The beam induced dark current in the samples was measured and found negligible, as expected: the 62 MeV protons do not produce Čerenkov light in quartz.

The result, expressed in terms of transparency of 1 m of fiber as a function of time, divided by the transparency before irradiation, is shown in Figure 3.

The samples were irradiated during 10 hours, with three 20-30 min periods without beam (and one 9 min period because of accelerator problems). These periods are clearly visible in the Figure, due to fast annealing of transparency loss. The radiation doses corresponding to the moments of beam stops were calculated on the basis of the theoretical dose rate and beam time, and have a common systematic uncertainty of ∼10%. The total dose, 825 krad, roughly corresponds to the maximum dose accumulated by the clear fibers in ECAL after 5–10 years of work.

In Figure 3 one can see the fast degradation and fast annealing cycles corresponding to stopping and resuming of irradiation. The magnitude of transparency variation in these cycles depends on the previously accumulated dose; of course it should depend also on the dose rate. The annealing lasts ∼10–20 minutes; there is no significant change of transparency during 12 hours after the test. The transparency value after annealing does not return to the initial value, there is a non-zero residual damage. Its dose dependence is shown at the insert in Figure 3, it is roughly linear.

For the LHCB ECAL application, the expected maximum dose rate for fibers will not exceed 0.01 rad/s, which is more than three order of magnitude less than at the irradiation test. Therefore the relevant value of fiber transparency degradation is expected to be very close to the residual one. Both types of fiber therefore satisfy our requirement of degradation not exceeding 1% per metre for 100 krad.

The direct measurement of the dose rate dependence of the fiber transparency variation is planned for July 2014 in UCL using our fiber samples which were irradiated there during the test in 2013.

5. Status of the upgrade work

The work on the ECAL monitoring system upgrade started in October 2013 with production of the new bundles of light guides made of quartz fiber. This work was performed at CERN. The main difficulty was that it was not possible to use standard fiber optic connectors, we had to develop and produce custom connectors to fit the optical inputs on existing ECAL modules. The bundle production has finished in February 2014.

The installation of bundles to ECAL took 3 months, February–April 2014. The commissioning phase for the moment (May 2014) is close to the end: all the cells are operational, the last thing
left to do is to tune the amplitude and timing of LED flashes.

Few highlights from the bundle production, installation and commissioning are shown in Figure 4.

6. Conclusion
The accuracy of the present LED monitoring system of the LHCb ECAL appears to suffer from radiation damage of the light guides transporting LED light to PMTs and made of plastic clear fibers (KURARAY Clear-PSM). The upgrade consisting in replacement of the light guides to radiation tolerant ones made of quartz fiber will allow for the PMT gain following within few % accuracy. The upgrade work was finished in May 2014.

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