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Upgrade of the LHCb RICH detectors and characterization of the new opto-electronics chain

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ABSTRACT

The LHCb detector has been upgraded to manage a five-fold increase in the instantaneous luminosity delivered to the experiment during LHC Run 3 and to readout data at the full bunch crossing rate of 40 MHz. The enhanced LHCb RICH detectors now feature Multianode Photomultiplier Tubes (MaPMTs), covering a total area of approximately 4 square meters, and brand-new frontend electronics to comply with the trigger-less readout architecture. The opto-electronics chain is capable of detecting single photons at repetition rates of up to 100 MHz/cm^2 while maintaining an exceptionally low noise. The RICH upgrade is comprehensively outlined, including details about the characterization and studies on the photon detection system. The stability and uniformity achieved by optimizing the parameters of the opto-electronics chain enable the RICH system to function successfully and to provide excellent charged hadron identification in high occupancy conditions.

1. Introduction

The LHCb experiment at CERN's Large Hadron Collider (LHC) is designed to search for new physics beyond the Standard Model by studying b and c quark decays. It operates as a single-arm forward spectrometer covering the pseudorapidity range of $2 < \eta < 5$, and is equipped with advanced tracking and particle identification detectors optimized for detecting c- and b-hadrons. High performance in particle identification (PID) is critical for LHCb, achieved through the Ring Imaging Cherenkov (RICH) system, which provides excellent charged hadron identification over a wide momentum range. The RICH system includes two sub-detectors: RICH 1, located near the interaction point, covers the momentum range 2–50 GeV/c, while RICH 2, positioned after the tracking system, 15–100 GeV/c. These detectors utilize C_4F_{10} and CF_4 gas radiators, respectively, to generate Cherenkov photons, which are focused by a mirror system onto single-photon-sensitive detectors.

To support data readout at the 40 MHz LHC bunch crossing rate and luminosity of $2 \cdot 10^{33}$ cm^{-2} s^{-1}, LHCb has upgraded its systems during the LHC's long shutdown 2 (2019–21). The RICH detectors, which have performed exceptionally well during LHC Run 1 and Run 2, required significant enhancements to keep the same PID performance at five times the luminosity.

2. MaPMTs as LHCb RICH upgrade photo-sensors

Multianode Photomultiplier Tubes (MaPMTs), shown in Fig. 1, were chosen as the optimal candidates for the LHCb RICH photo-sensors since they fulfill all the desired requirements:

- Single-photon detection at the 40 MHz LHC bunch crossing rate: this is achieved through the appropriate MaPMTs deadtime and their coupling with the CLARO ASIC [1].
- Handling detection rates around 100 MHz/cm^2: the MaPMTs' large active area (≈80%) and spatial granularity (≈10 mm^2) minimize inefficiencies and pixel size errors, aiding in the separation of overlapping rings.
- Suitable gain and quantum efficiency: with gains higher than 10^6 electrons (Section 3) and quantum efficiency over 30% at 300 nm, MaPMTs maximize photon yield per charged particle and control chromatic uncertainty.
- Low dark count rate: MaPMTs maintain a dark count rate around 10 kHz/cm^2, alongside minimal internal instrumental noise.

In the high occupancy regions, MaPMTs exhibit gain non-linearity due to increased anode current resulting in interstage voltage changes. To mitigate this effect, the last dynode is powered independently at the

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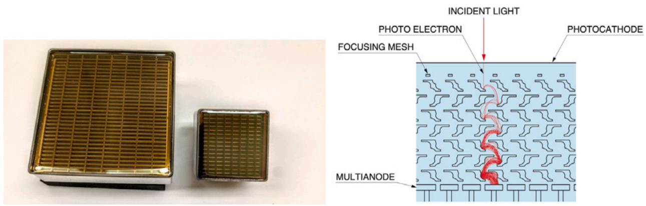

Fig. 1. Left: the MaPMT types selected for the upgraded RICH detectors with the 2-inch model on the left and the 1-inch model on the right. Right: scheme of the internal structure of the MaPMT.

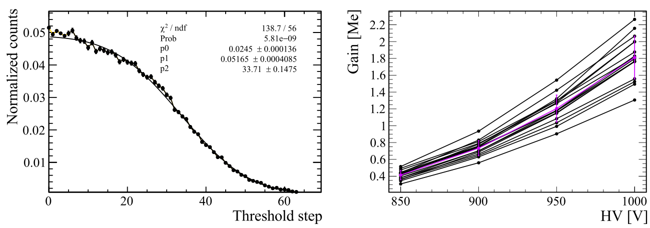

Fig. 2. Left: integrated charge spectrum from the threshold scan for a single RICH 1 anode. Right: k-factor for a RICH 1 PDM. The black lines are the single MaPMTs' k-factors, the violet line is their average representing the PDM's k-factor.

nominal HV value, monitored outside the collision time. This precise control enables the measurement of luminosity via the MaPMT anode current (Section 4).

3. Gain equalization studies

A uniform MaPMT response across the whole photo-detection plane can be achieved by equalizing the MaPMTs gain. This is achieved through threshold scans, where a threshold can be defined as the charge level of the CLARO ASIC discriminator over the baseline: the current pulse from a MaPMT anode triggers a digital output if the charge amplitude of the signal is above threshold. Such procedure allows a fine-tuning of the High Voltage (HV) settings, while repeated threshold scans can be used to monitor the ageing of the photosensors checking the gain variations, as explained in the following. A threshold scan is acquired in beam on conditions for each MaPMT channel (about 200,000 channels across RICH 1 and RICH 2 sub-detectors), providing the trend of normalized count rates vs threshold displayed in Fig. 2, left. The normalized count rate is proportional to the integral of the beam-generated current-pulse of the MaPMTs, thus it is possible to interpret Fig. 2, left, as an integrated charge spectrum. Such distribution is fitted with an *erf* function and the flex is extracted (where the flex is defined as the threshold at which the second derivative of the fitting function changes sign). Given that the fitted distribution is an integrated charge spectrum, the flex can be interpreted as a gain estimation. This procedure is repeated for different HV settings in order to extract the k-factor curves, which model the gain dependence with the HV (Fig. 2, right). By the RICH subdetectors design, the MAPMTs are grouped in the so called Photo Detection Modules (PDM). The HV can be tuned only at the PDM level, thus one k-factor is extracted for each PDM. By means of the k-factors it is possible to choose a target gain to uniform all the photo-detection planes: in this way it is possible to obtain the fine-tuned HV settings.

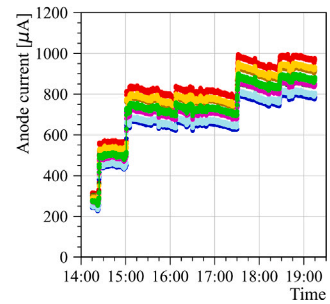

Fig. 3. Anode currents variation during a μ scan. The different colors stand for 7 PDMs in the RICH 1 high occupancy region, as an example.

4. Luminosity measurement

The RICH sub-detectors can provide a stand-alone luminosity measurement for the LHCb experiment. Thanks to the use of MaPMTs, it is possible to evaluate the luminosity by estimating the anode currents and cross-calibrating them with the number of Cherenkov hits.

Exploiting the number of Cherenkov hits, the luminosity can be computed as $L = \frac{\mu_{vis}}{\sigma_{vis}} \cdot n_{bb} \cdot \nu_{LHC}$: μ_{vis} is the number of visible interactions per bunch crossing, computed as $-log(N_{empty}/N_{events})$ following Poisson statistics; σ_{vis} is the visible cross section at the PDM level; n_{bb} is the number of bunch crossings; ν_{LHC} is the LHC bunch crossing rate.

The luminosity is calibrated during Van der Meer scans, where the separation of the two proton beams is varied in the x and y directions. This allows the estimation of the visible cross section σ_{vis}. Such information is also exploited during μ scans, where the number of proton–proton interactions per bunch crossing is varied over time.

The luminosity extraction via the measurement of the number of Cherenkov hits can be used to calibrate the RICH MaPMT anode currents, which are sensitive and proportional to the luminosity (Fig. 3). The capability to monitor such quantity via the anode currents provides an immediate online estimation. The extraction of the luminosity via the number of Cherenkov hits allows for a more refined offline analysis.

5. Conclusions

The LHCb RICH detector upgrade effectively meets the challenges of a five-fold increase in instantaneous luminosity, maintaining robust performance at the 40 MHz bunch crossing rate. Key improvements include enhanced photon detection with MaPMTs and new front-end electronics, detailed noise characterization and mitigation, and innovative luminosity evaluation by correlating MaPMT anode currents with Cherenkov hits. These advancements ensure excellent PID performance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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