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The upgrade and performance of the LHCb RICH detector

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Summary. — The LHCb experiment at CERN studies b and c hadrons decays in the forward region. Many physics analyses in LHCb rely on the Ring Imaging Cherenkov (RICH) detector for the charged-hadron identification in a wide momentum range. The RICH detector is currently undergoing a substantial upgrade: an improved optics and multi-anode photomultipliers, coupled with new readout electronics, will deal with the expected five-fold increase of luminosity in RUN 3, starting in 2021. Upgrade activities will be presented, including hardware characterization and expected improvements in the detector performance.

1. – Introduction

LHCb is one of the four main experiments installed at the Large Hadron Collider (LHC) at CERN [1], dedicated to the study of CP violation and rare decays of b and c hadrons. During the LHC Long Shutdown 2 (LS2: 2019-2021) the LHCb experiment is undergoing a major upgrade [2] to improve the precision of its measurements and its discovery potential. In 2021 the luminosity will increase up to a value of $\mathcal{L} = 2 \times 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$, a five-fold increase compared to the previous conditions, and the readout of all the sub-detectors of LHCb will operate at 40 MHz bunch crossing rate, to be compared with the 1 MHz readout rate achieved before LS2. Hadron Particle Identification (PID) in LHCb is performed by two Ring Imaging Cherenkov (RICH) detectors, both detectors have an optical system that redirects the Cherenkov light produced by the particles towards the photodetector planes and outside the acceptance of the spectrometer. RICH 1 is the Cherenkov detector closer to the interaction point, it covers the full LHCb angular acceptance (300 mrad $\times$ 250 mrad) and it is filled with C_4F_{10} gas. RICH 2 is placed downstream of the spectrometer magnet, it is filled with CF_4 and it covers an angular acceptance of 120×100 mrad. Overall, the RICH system provides PID in the momentum range 2–100 GeV/c.

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2. – The LHCb RICH upgrade

During Run 1 and 2 (before LS2) the readout rate was limited to 1 MHz after the L0 trigger, the new working condition at 40 MHz imposes to modify front end electronics of all sub-detectors. The interesting events selection will be performed by a software-based trigger on a PC farm to enhance event selection efficiency.

The LHCb RICH detectors have provided a reliable and robust performance during LHC Runs 1 and 2 [3, 4]. The higher luminosity expected in the upcoming LHCb run implies an increase of the particle multiplicity in a bunch crossing and a higher dose of radiation. To face these new challenges and maintain excellent performance, some upgrades are needed. The overall structure of the RICH detector will remain unchanged with few modifications in the RICH 1 optical system and the Hybrid Photo Detectors (HPDs) will be replaced by Multi-Anode PhotoMultiplier Tubes (MaPMTs) in both RICH1 and RICH2.

2·1. *Optics and geometry.* – The occupancy values need to be controlled in order not to degrade the PID performance. With the current RICH 1 configuration and the expected luminosity of $\mathcal{L} \sim 2 \times 10^{33}$ cm^{-2}s^{-1}, occupancy will increase up to 50%. To reduce this value with the new luminosity, some changes in the optical layout of RICH 1 will take place. The position of the focal plane will be adjusted and the radius of curvature of the spherical mirrors increased to obtain a magnification of the Cherenkov rings in the plane of the detectors (and hence decrease occupancy). In the upgraded geometry, the photodetectors will also be placed further inside the magnetic shielding.

2·2. *Photodetectors and Electronics.* – The HPDs installed for Runs 1 and 2 have the readout electronics encapsulated in the vacuum tube with a trigger of 1 MHz, so they are not suitable for the new working requirements. MaPMTs coupled a customized readout electronics which can sustain a 40 MHz rate will be installed instead. Two types of MaPMTs are considered, 1×1 inches R13742 Hamamatsu MaPMTs for high occupancy region and 2×2 inches R13743 Hamamatsu MaPMTs for low occupancy region. The readout will be performed by the CLARO chip [5], an 8-channel amplifier/discriminator ASIC. The electronics have been tested against radiation damage to ensure they can operate successfully [6]. MaPMTs are integrated with Front End Boards and the CLARO chip in a compact device called Elementary Cell (EC), two types of EC have been developed, type R (EC-R) and type H (EC-H), which respectively host four MaPMTs of 1×1 inches and one MaPMT of 2×2 inches. Ann EC-R is shown in fig. 1. More ECs will constitute the Photo Detector Modules (PDM) which will interface with the new LHCb readout through Photo Detector Module Digital Board (PDMDB). PDMs are the fundamental modules of the RICH columns which will form the photodetector planes of the LHCb RICH. This level of modularity of the detector facilitates maintenance and operations.

3. – Quality assurance

All the components which will constitute the LHCb RICH detector, from the basics components to the assembled ones, have to be tested to assure reliability and conformity. All MaPMTs have been characterized [7] and classified concerning their main characteristics (*e.g.*, average gain and dark count rates). The same HV will be supplied to the MaPMTs of the same PDM and the installation of MaPMTs with a similar gain allows

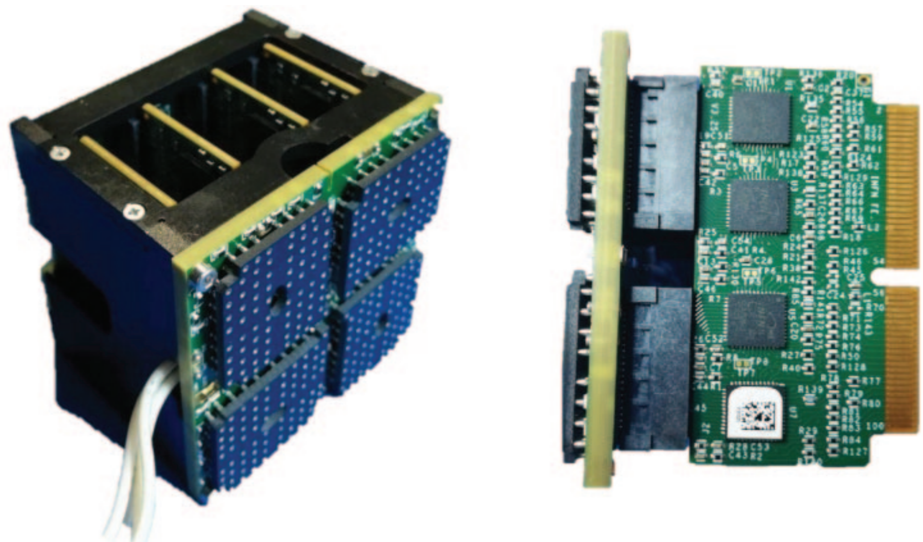

Fig. 1. – Left: an assembled EC-R. Right: a view of an EC-R from the side without case and backboard, the CLARO chips are soldered on the front end boards.

uniformity of response, a fine-tuning can be achieved by adjusting the settings of CLARO channels for each MaPMT pixel.

A quality assurance procedure has validated the main electronics components, meaning the CLARO ASICs chips and front end boards. After being accepted, the components are assembled into EC. All the ECs needed to pass an established test protocol. Four testing stations have been deployed between Ferrara and Edinburgh. Each station consists of a light-tight box that hosts the ECs during testing. A DAQ control software, developed in LabView, allows to control of the HV supply and a LED driver, to configure the electronics (Digital Boards and CLARO chips), and to run an automated test on the ECs. The validation of an EC consists of measurements that verify the conformity of FEB and CLARO, and also monitor dark count rates and afterpulses of the MaPMTs installed on the ECs.

4. – Upgrade performance

The quality of the PID relies on the accurate measurement of the Cherenkov angle of the charged particle while particle direction and momentum are known by the tracking system. The Cherenkov angle reconstructed from the light emitted by particles has a resolution expressed in mrad. The main contributions to the angular resolution are the chromatic effect, the emission point error and the pixel contribution. The chromatic effect is caused by the variation of the refractive index of the radiator as a function of the photon wavelength. The emission point error is related to the spread of the Cherenkov angle caused by mirror aberration and physical constraints on the mirrors. The pixel contribution depends by the photodetectors size and granularity instead. In table I the contributions to the angular resolution are reported for HPDs and MaPMTs: an improvement is expected in the chromatic error (the quantum efficiency of MaPMTs peaks at higher wavelength respect to HPDs), in the pixel resolution (no point spread

TABLE I. – *The main components of the Cherenkov angle resolution expressed in mrad. In RICH2, two types of MAPMTs (1×1 and 2×2 inches) with different pixel sizes will be mounted, hence two different values of pixel contribution are reported. In RICH 1 only 1×1 inches MAPMTs will be used.*

Source	HPD - RICH 1	MaPMT - RICH 1	HPD - RICH 2	MaPMT - RICH 2
Chromatic	0.84	0.58	0.48	0.31
Pixel	0.60	0.44	0.19	0.19 (0.40)
Emission point	0.76	0.37	0.27	0.27
Total	1.60	0.78	0.65	0.45

function contribution in the case of MaPMTs) and in the emission point thanks to the improved optics. A time gating will be also applied in Run 3 [8]. The signal on the RICH detector plane produced by photons generated in an LHC bunch collision fits in a time interval that depends on the size of the proton bunch. The width of the signal corresponds to a few ns, while the time interval between two bunch crossing at 40 MHz is 25 ns. A time gate of 6.25 ns can be applied to reduce the continuous background through the FPGA on the front end digital boards by sampling the CLARO chip output.

5. – Conclusions

The LHCb RICH Upgrade is successfully ongoing. The quality assurance procedure has validated both electronics and MaPMTs, the components have been delivered to CERN. The installation of RICH 2 has been completed in early 2021 and the commissioning of RICH 1 is proceeding successfully to provide a fully operational RICH system for the start of Run 3.

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