

The LHCb RICH detector upgrade: Improvements and expected performance

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Summary. — LHCb is one of the main experiments running at the CERN Large Hadron Collider (LHC) and is specialized in heavy-flavour physics. One of its key detector components is the Ring-Imaging Cherenkov (RICH) system which has the crucial task of identifying charged particles over a wide momentum range. During the Long Shutdown 2 of the LHC (2019–2022), the RICH detector has been undergoing a significant upgrade with the installation of new photodetectors, electronics and modified optics and mechanics. This will allow handling a higher luminosity and 40 MHz continuous data taking, expected for Run 3. The current status of the RICH upgrade will be reviewed starting from a summary of the major changes to the presentation of the expected improvements in detector performance.

1. – Introduction

The LHCb experiment performs high precision measurements including CP-violation, rare decays, precision Standard Model (SM) measurements and search for physics beyond SM. The detector is a single-arm forward spectrometer fully instrumented in the pseudorapidity range $2 < \eta < 5$, optimised for the detection of c- and b-hadrons [1].

High performances in particle identification (PID) are essential for any high-energy physics experiment. At LHCb, this is achieved by the Ring Imaging Cherenkov (RICH) system which delivers excellent charged hadrons identification in a large momentum range. The RICH system consists of two sub-detectors. The RICH 1 detector is located upstream of the LHCb magnet and is based on a C_4F_{10} gas radiator for particle momenta ranging from 10 to 65 GeV/c. The RICH 2 detector is placed downstream of the magnet and makes use of a CF₄ gas radiator, allowing for hadron PID in a momentum range from 15 to 100 GeV/c. Cherenkov photons generated in the gas radiator are focused onto

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an array of single-photon-sensitive detectors by the RICH mirror system, which consists of a tilted spherical mirror followed by a plane mirror.

The LHCb RICH detectors have performed exceptionally well during the LHC Run 1 and Run 2. For the upgrade of the LHCb experiment, significant changes are needed to maintain the level of particle identification at a five times higher luminosity.

2. – The upgrade of the RICH detector system

The LHCb detector is currently undergoing a major upgrade to enable the experiment to run at a luminosity of $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ and read out data at a rate of 40 MHz into a flexible software-based trigger [2]. The challenges induced by the higher luminosity are: an increment of the particle multiplicity per bunch crossing and a larger radiation dose. Furthermore, with the removal of the previous 1 MHz hardware trigger, the RICH read-out electronics have to provide single-photon counting capability at 40 MHz and compensation for the typical pixel gain variation.

In order to cope with these new experimental conditions, both RICH detectors have been upgraded with modified mechanics, new spherical mirrors, and a redesigned opto-electronic system.

2.1. Mechanics and optics. – Mechanics and optics in RICH 1 have been adapted to deal with the higher detector multiplicity. In order to maintain performance, the peak occupancy in a single photo-detector channel has to be kept below 30%, therefore it is necessary to spread the photon distribution over a wider area. This is achieved by increasing the radius of the spherical mirrors to 3.7 m with respect to the previous value of 2.7 m [3]. In addition, the focal plane has been moved backwards resulting in overall enlargement of the Cherenkov ring size. In this configuration, the photodetectors are placed deeper inside the magnetic shielding.

2.2. Photon detection system. – The Hybrid Photon Detectors (HPDs) have been replaced with two models of Multi-Anode Photo-Multiplier Tubes (MaPMTs) with 8×8 channels from Hamamatsu: the 1-inch R13742, used in RICH 1 and the central part of RICH 2, and the 2-inch R13743 for the outer areas of RICH 2. The MaPMTs show a single photon spectrum typically well distinguishable from the noise, a low dark count rate, a minimum gain of 10^6 at 1 kV, and pixel-to-pixel gain variation of 1:3 [3].

The front-end boards feature custom read-out ASICs called CLARO, an 8-channel chip containing an analogue pulse shaping amplifier and a binary discriminator allowing the detection of single photons. The signal is amplified and digitised while the threshold can be set for each channel individually [4]. Then, the output of the CLARO is fed into an FPGA, which synchronises the data with the LHC clock and transmits the events, through a GigaBit Transceiver (GBT) link, to the High Level Trigger (HLT) stage [5].

The combination of the MaPMTs, the front-end electronics, and the digital board is called the Elementary Cell (EC), which is the basic unit of the photon detection system. There are two types of ECs, type R and type H, which respectively host four 1-in. MaPMTs and one 2-in. MaPMT (see fig. 1).

2.3. Timing for background rejection. – In the RICH environment, the photon time-of-arrival (ToA) distribution peaks around a specific value and has a small spread, thanks to the prompt Cherenkov radiation and the optical system. With timing information, it is possible to select a photon signals in a well defined ToA interval and reduce out-of-time background by applying a time gate to the front-end electronics. This is realised with

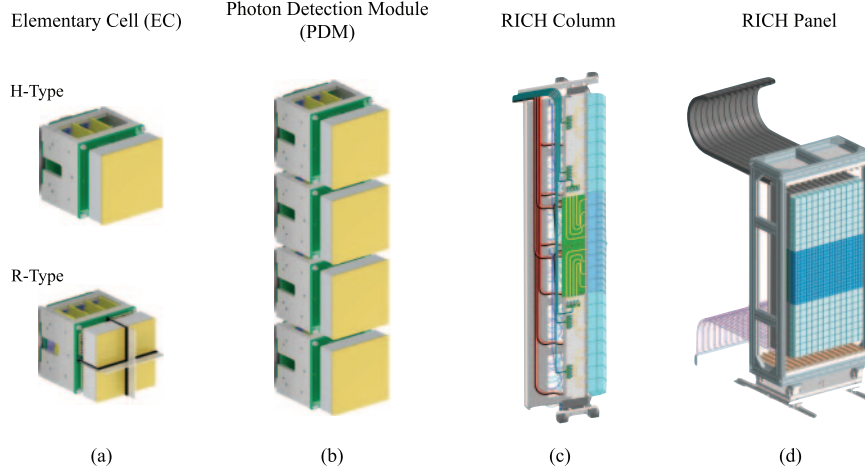


Fig. 1. – CAD models of the fundamental units of the LHCb RICH detectors. MaPMTs, front-end electronics, and backboards form an H- or R-type EC (a). Four ECs with 2 Digital Boards constitute the Photo Detector Modules (PDM) (b), the fundamental parts of the RICH columns (c) which form the photodetector planes (d) of the RICH system. This modular structure ensures efficient replacements and monitoring operations.

the FPGA in the read-out system which is adapted to sample the CLARO signals at 320 MHz and to apply the time gate to a specific input pattern [6]. Recent beam tests at the CERN SPS have shown that using a time gate of 6.25 ns can increase the signal-to-noise ratio by a factor of three to four, thus improving the efficiency of the RICH pattern recognition algorithms [5].

3. – Expected performance

An accurate measurement of the Cherenkov angle is a fundamental requirement to improve the PID performances. Typically, in a RICH detector there are three main contributions that worsen the Cherenkov angle resolution: detection point error (pixel size), emission point error and chromatic error. A summary of the different contributions is reported in table I.

In RICH 1, the precision of the detection position is improved, as a result of a higher detector granularity, provided by the smaller pixel size of the MaPMTs. Furthermore,

TABLE I. – *Expected components of the Cherenkov angle resolution for the upgraded RICH detector system compared to the previous one.*

Resolution (in mrad)	RICH 1-2015	RICH 1-upgrade	RICH 2-2015	RICH 2-upgrade
Pixel	0.60	0.44	0.19	0.19
Emission point	0.76	0.37	0.27	0.27
Chromatic	0.84	0.58	0.48	0.31
Total	1.60	0.78	0.65	0.45

the emission point uncertainty caused by mirror aberrations and geometrical constraints, decreases by a factor of two with the new geometry. The chromatic error is reduced in both RICH detectors thanks to the MaPMT quantum efficiency curve, which peaks at longer wavelengths than that of the HPD. Overall, the total angle resolution for RICH 1 is improved by a factor of two, and for RICH 2 it is reduced by 20 mrad.

4. – Quality assurance and commissioning

The new components of the upgraded RICH detector have to pass a precise quality assurance procedure in order to guarantee performances for the next ten years. All the MaPMTs and the CLARO ASICs have been characterised individually and tested again after being assembled in the ECs. In particular, the EC's validation procedure is a set of automated measurements to monitor dark count rates and afterpulses of the MaPMTs, verify the basic functionality of the front-end electronics, and test if radiation hardness is compatible with the upgrade requirements (200 krad , $3 \times 10^{12} \text{ 1 MeV } n_{eq}/\text{cm}^2$, $1.2 \times 10^{12} \text{ HEH}/\text{cm}^2$) [7].

After passing the protocol, the ECs are delivered to CERN for the column assembly and the commissioning operations. This final part envisages several steps (mechanical mounting, low- and high-voltage cabling, checks on hardware and fibre connections, installation and monitoring of the cooling system, etc.) and it is crucial to verify that the complete opto-electronic chain is working properly and fits in the LHCb upgraded environment.

5. – Conclusions

During the LHC Long Shutdown 2 (2019–2022), many efforts have been done to provide an operational upgraded RICH system for starting Run 3. The RICH 2 detector is now fully installed and it successfully took part to the LHC beam test campaign in October 2021, observing the first Cherenkov rings from particle collisions. The RICH 1 spherical and flat mirrors are installed and aligned, and column commissioning is almost completed.

REFERENCES

- [1] THE LHCb COLLABORATION, *J. Instrum.*, **3** (2008) 08.
- [2] THE LHCb COLLABORATION, *LHCb PID Upgrade Technical Design Report*, CERN-LHCC-2013-022 (2013).
- [3] FIORINI M., *Nucl. Instrum. Methods A*, **952** (2020) 161688.
- [4] BASZCZYK M. K. *et al.*, *J. Instrum.*, **12** (2017) P01012.
- [5] PAPANESTIS A. *et al.*, *J. Instrum.*, **15** (2020) C09022.
- [6] KEIZER F., *Sub-nanosecond Cherenkov photon detection for LHCb particle identification in high-occupancy conditions and semiconductor tracking for muon scattering tomography*, PhD Thesis, University of Cambridge (2020).
- [7] ANDREOTTI M. *et al.*, *Radiation hardness of the CLARO8 ASIC: A fast single-photon counting chip for the LHCb experiment at CERN*, in *IEEE Radiation Effects Data Workshop* (IEEE) 2017, pp. 1–4.