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The LHCb RICH detectors between present and future

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Summary. — During Run1 and Run2 the two RICH detectors operated continuosly at the luminosity of $\sim 4 \times 10^{32}$ cm^{-2}s^{-1} and provided an excellent particle identification information (PID) for final-state charged hadrons. In order to be able to operate at the luminosity of $\sim 2 \times 10^{33}$ cm^{-2}s^{-1} from the start of Run3 in 2021 the two RICH detectors must be upgraded; the former HPD (Hybrid Photon Detectors) will be replaced by commercial MaPMTs, the optics of the upstream RICH will be modified and the electronics will be upgraded to cope with the challenges of the 40 MHz readout rate. In this paper the current status of the upgrade will be presented. The start of the HL-LHC phase in 2027 provides an opportunity to increase the luminosity up to $\sim 10^{34}$ cm^{-2}s^{-1}. To be able to operate the RICH detectors in this much harsher environment a further upgrade will be mandatory; in this paper possible photodetector candidates will be discussed along with new ideas to improve the PID efficiency using time information.

1. – Introduction

LHCb is one of the four main experiments operating at the LHC and it is dedicated to measurements of CP violation and to the search for new physics beyond Standard Model in the rare decays of hadrons containing heavy quarks [1].

Until the end of Run2 the hardware trigger system of LHCb limited the data acquisition rate to a maximum of 1 MHz [2]. From the beginning of Run3, the trigger system of the experiment will change considerably and, in particular, the Level 0 hardware trigger will be removed to allow a data readout at the full rate of 40 MHz [3].

The resulting increase in data acquisition rate will allow for significant improvements in efficiencies, in particular for hadronic decays, which are crucial for the study of many rare decays.

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Particle identification informations at LHCb are provided by two Ring Imaging Cherenkov systems, RICH1 and RICH2, which operate in the momentum range 1–100 GeV/c [4]. In order to adapt the RICH system to the new trigger system the HPD detectors with embedded readout electronics limited to 1 MHz will be replaced; multi-anode photomultipliers with external readout electronics will be used instead.

2. – The upgraded photodetector system

The photodetecting unit used in the upgrade consists of a 8×8 pixel MaPMT produced by Hamamatsu Photonics. It features a 12-dynode amplification stage with a nominal gain factor of 10^6 at the working tension of 1 kV and a low dark count rate at ambient temperature. The quantum efficiency of the MaPMTs is shifted towards the green wavelength region with respect to the HPDs which has the effect of improving the resolution on the Cherenkov angle by reducing the chromatic error.

Two different types of MaPMTs will be used: the R13742 type and the R13743 type. The R13742 type has a $2.8 \times 2.8\,\mathrm{mm}^2$ pixel size and will cover the entire RICH1 and the central part of RICH2, whereas the R13743 type has a $5.6 \times 5.6\,\mathrm{mm}^2$ pixel size and will cover the outer part of RICH2.

The choice of using MaPMTs with bigger pixels in the outer part of RICH2 is motivated by the significant decrease in the photons rate with respect to the central part closer to the beam line. This has the benefit of reducing the number of readout channels with negligible impact on the performance.

The analog signal produced by the MaPMTs at the anode is shaped and amplified by the CLARO [5], an 8-channel ASIC realized in 0.35 μm AMS CMOS technology, with a recovery time shorter than 25 ns. Each channel is equipped with a 6-bit programmable threshold and a 2-bit programmable gain.

The MaPMTs and the CLARO chip will be assembled in compact structures called Elementary Cells (ECs). In the RICH upgrade two types of EC will be installed: the R-type EC, composed of 4 R13742 MaPMTs, and the H-type EC, composed of a single R13743 MaPMT.

The ECs are connected to the PDMDB (Photon Detector Module Digital Board), as shown in fig. 1.

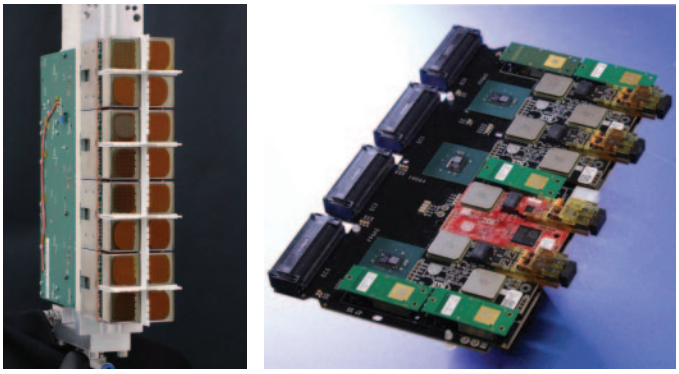

Fig. 1. – Left: the photo detector module with the 4 R-type ECs. Right: A PDMDB with the 3 FPGAs and the optical links.

Each PDMDB serves 4 ECs and handles the data packing and streaming via optical links to the DAQ board. In the final configuration RICH1 will have 22 columns with 12 PDMDBs each whereas RICH2 will have 24 columns with 8 PDMDBs each.

3. – Optimization of the optical design

During the Run1 and Run2 phase some regions of the photon detector array in RICH1 reached occupancies of up to 30%. Occupancy is defined as the fraction of detected photons over the total number of channels; the 30% value for the occupancy is seen as an upper limit beyond which the particle identification performance of the RICH starts to deteriorate.

In order to maintain the average occupancy of the old RICH detector in the upgraded configuration where the luminosity increases by a factor five some minimal changes in the optical system are required [6]. This is accomplished by increasing the focal lenght of the sferical mirror by a factor $\sqrt{2}$ and moving the photo detector plane further away from the beam line as shown in fig. 2.

Moreover, a slight re-arrangement of the spherical mirror configuration as shown in the figure allows to decrease the emission point uncertainty and, consequently, improve the overall resolution of the Cherenkov emission angle. The final resolution is expected to be 0.88 mrad for Run1, which is nearly a factor 2 improvement with respect to the previous configuration, and 0.60 mrad for RICH2.

4. – The RICH detectors in a HL-LHC scenario

A further jump in luminosity to $\sim 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ during the HL-LHC phase would imply an increase in occupancy by a further factor 5. Magnifying the image on the detector plane by the same factor would imply enormous costs and the need for a larger volume inside LHCb. Instead, a reduction of the pixel size down to $1\,\mathrm{mm}^2$ seems to be more realistic.

Timing information may also be used to further improve the PID [7]. From simulation it is shown that time resolution of 1 ns for the photon arrival, which translates into a 150 ps resolution per "ring" when 40 photons are considered, is sufficient to obtain a significant improvement of the PID performance. Since the true Cherenkov photons resulting from proton-proton collisions reach the detector within 1 ns time window, as

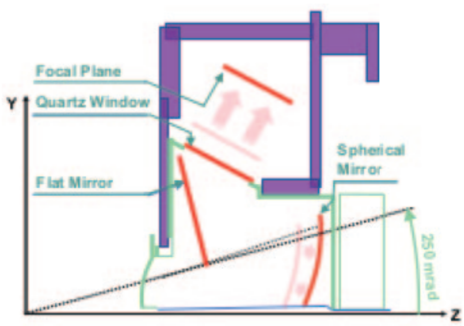

Fig. 2. – Schematic side view of the upper half of the RICH1 detector after the upgrade with indicated mechanical modifications to increase the focal length.

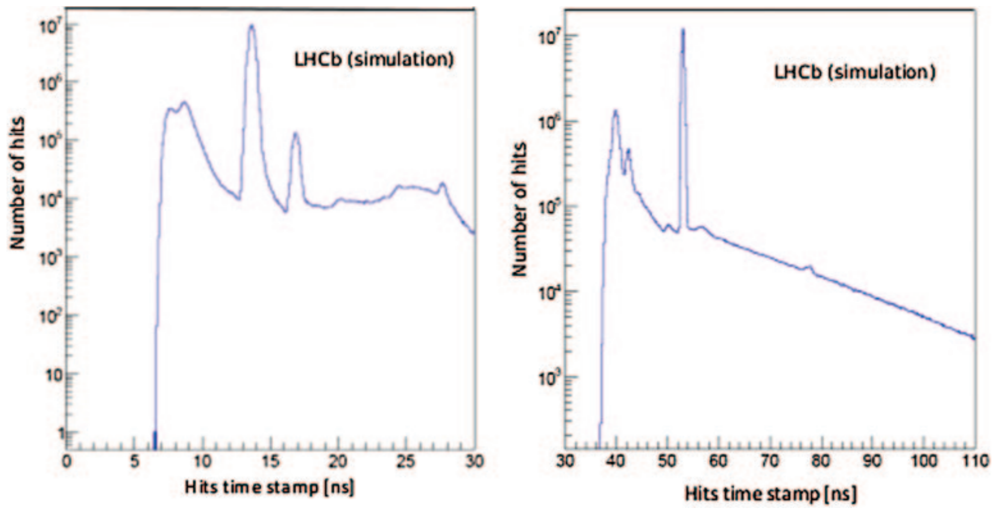

Fig. 3. – Left: simulated hit arrival time distribution on RICH1 photodetector arrays (left) and RICH2 (right). The main peak is due to hits from particles originating in the proton-proton collisions.

shown in fig. 3, the timing information would also help get rid of the background photons falling outside this window more efficiently.

Among the possible commercial photodetector candidates with small enough pixel size and sufficiently low time resolution to comply with these requirement are SiPMs (Silicon Photomultipliers) and MCP (Micro Channel Plates). SiPMs would be ideal devices due to their better quantum efficiency spectrum with respect to PMTs, relatively low time resolution of ∼200 ps, comparable high gain at much lower working tension and insensitivity to magnetic fields but are, in turn, more sensible to radiation damage and have a high dark count rate at room temperature.

Tests of SiPMs irradiated up to 10^{14} $n_{eq}/\,\mathrm{cm}^2$ have shown that single photon detection is possible if cooled to 77 K [8]. MCP, instead, feature a very low timing resolution of ∼50 ps, a quantum efficiency comparable to a PMT, a better radiation hardness, but are affected by early aging effects.

5. – Conclusions

The commissioning of the upgraded RICH detectors is about to enter the last phase before the restart of LHC in 2021. At the time of writing the assembly of the first RICH columns is well underway and automated procedures to test the quality are being finalized. The installation of the column as well as the modifications to the mechanical structure in RICH1 and the replacement of the old mirrors with new ones is due to begin in spring 2020.

In this paper ideas on how to operate the RICH detectors in the harsher environment of HL-LHC without a complete overhaul of the system have also been presented. Recent progresses in silicon photomultiplier technology and new cooling techniques to improve dark-count rates and lifetime of these devices appear to be very promising for a potential use in a future Upgrade 2 RICH.

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