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The upgrade of the LHCb RICH system for the LHC Run 3

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ABSTRACT: The RICH detectors of the LHCb experiment have provided particle identification with excellent performance during Runs 1 and 2 of the LHC. Currently the LHCb experiment is undergoing an upgrade to allow, starting from 2021, data collection at 5 times the instantaneous luminosity of the period 2010-2019 (up to $2 \times 10^{33}\text{cm}^{-2}\text{s}^{-2}$) with the aim to collect a data sample corresponding to $50\,\text{fb}^{-1}$. The required upgrades to detectors and electronics are significant, with the RICH system changing all of the photon detectors and a full replacement of the upstream RICH detector. The existing Hybrid Photon Detectors (HPD) are being replaced by two types of Multi-Anode Photomultiplier Tubes (MaPMT) with electronics capable of recording data at the full LHC collision frequency of 40 MHz using a time gate of 6 ns. The required 3072 MaPMTs have undergone detailed characterisation, measuring gain and uniformity across channels and the photo-cathode quantum efficiency on a smaller sample. The status of the project will be presented.

KEYWORDS: Cherenkov detectors; Particle identification methods

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1 Introduction

The LHCb experiment [1] at the Large Hadron Collider at CERN is currently undergoing an upgrade in order to operate at five times the current instantaneous luminosity, up to $2 \times 10^{33}\text{cm}^{-2}\text{s}^{-2}$. The goal of the experiment is to study CP violation and rare decays in b and c mesons. Most of the current measurements are statistically limited and the current upgrade is expected to significantly enhance the reach of the experiment for physics beyond the Standard Model. To achieve this and still trigger efficiently the 1 MHz hardware L0 trigger is removed and data will be transported to the High Level Trigger (HLT) computer farm at the 40 MHz collision rate.

Hadron particle identification (PID) in LHCb is performed by two Ring Imaging Cherenkov (RICH) detectors [2]: RICH 1 situated just after the Vertex Locator, covers the full 300 mrad acceptance of the spectrometer and uses C_4F_{10} as the gas radiator providing good PID in the momentum range 2–60 GeV/c. RICH 2 is located after the tracking stations, it covers 15–120 mrad acceptance, uses CF_4 and provides PID up to 100 GeV/c. Both detectors have a set of spherical mirrors to focus the Cherenkov light and a set of flat mirrors to reflect the photons towards the photon detectors situated outside the acceptance of the spectrometer.

2 The LHCb RICH upgrade

The LHCb RICH detectors have provided excellent performance [3] during the LHC runs 1 & 2 (an example can be seen in figure 1). For the upgrade of the LHCb experiment significant changes were needed to maintain (or possibly improve) the current particle identification performance at five times the luminosity [4]. The challenges of the increased luminosity are: far more complex events (with multiple proton-proton interactions per bunch crossing) and higher radiation dose for photon

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detectors, electronics and mechanical components especially those using composite materials. The removal of the 1 MHz hardware trigger also poses challenges in the speed of the electronics and the amount of data transported from the experiment to the HLT farm.

2.1 Detector geometry

To maintain performance with more complex events and higher detector occupancy the geometry of the optical elements of RICH 1 was modified to distribute the photons over a wider area, while at the same time improving the Cherenkov angle resolution. This is achieved by using a spherical mirror with a longer focal length and a smaller tilt to improve the emission point error. Using a longer focusing distance means that the photon detectors have to move further inside the magnetic shielding. The changes in the geometry can be seen in figure 2.

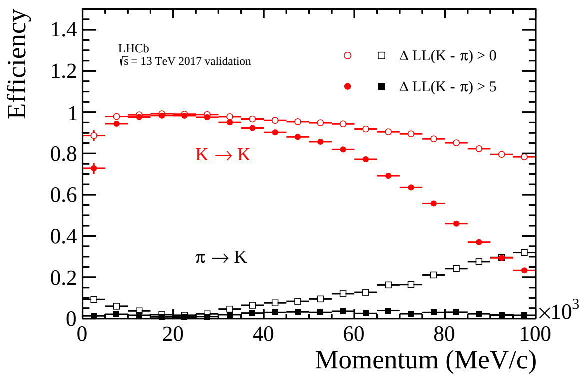

Figure 1. Pion-kaon separation efficiency and mis-identification versus momentum. The two sets of data correspond to two cuts on the log of the K/π likelihood ratio; the first optimised for efficiency, the second for purity.

2.2 Photon detectors and electronics

The Hybrid Photon Detectors (HPDs) that were used for Runs 1 & 2 have the readout electronics (including the 1 MHz trigger implementation) encapsulated in the vacuum tube and are incompatible

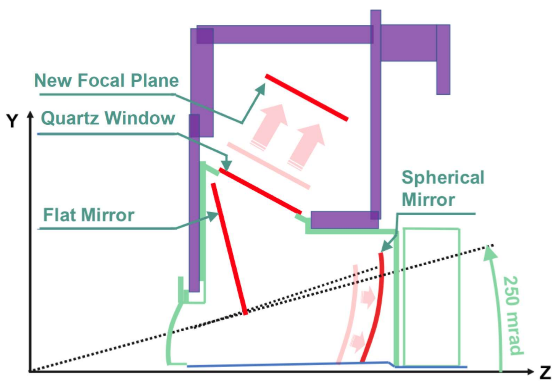

Figure 2. The new detector geometry for RICH 1. The spherical mirrors have been moved downstream and have a smaller tilt, and the photon detector plane has been pushed back inside the magnetic shielding.

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with the LHCb upgrade. The new photon detectors are two models of Multi-Anode Photo-Multiplier Tubes (MaPMTs) from Hamamatsu. The R12742 is a one-inch square tube with 64 channels (pixel size 2.9 mm) and will be used in RICH 1 and the central part of RICH 2, while the R13743 is a two-inch square tube (pixel size 6.0 mm) for the outer areas of RICH 2. The MaPMTs have good single photon response and very high active area. They are read out by a specially developed, radiation hard 8-channel amplifier-discriminator ASIC, the CLARO [5], with recovery time below 25 ns and therefore capable of operating at 40 MHz. The grouping of 4 small MaPMTs or one large one, together with the boards connecting it to the CLARO ASIC and the digital board is called the Elementary Cell (EC).

The output of the CLARO, which stays high while the input signal is above threshold, is captured by an FPGA, which synchronises the data with the LHC clock and transmits the events to the HLT farm via a GBT (GigaBit Transceiver) link. Having an FPGA in the readout system allows for extra flexibility as described in the following section. All the electronic components have been extensively tested to ensure they meet the radiation requirements of the experiment [6].

3 Using timing for background reduction

The prompt (emitted without time delay) Cherenkov radiation and focusing geometry of the RICH detectors results in an excellent intrinsic time resolution. The signal from a single proton-proton interaction fits within a window of 50 ps in RICH 1 and 500 ps in RICH 2 [7]. The larger time for RICH 2 is explained by the size and position of the detector. Within the LHC environment the time spread of the signal is dominated by the size of the proton bunch at the collision point [7] and the time distribution of the proton collisions within the same bunch. Figure 3 shows the time of arrival of photons at the RICH 1 photon detector plane following an LHC bunch crossing at time zero, simulated in the LHCb framework [8]. The width of the signal peak (labelled S in figure 3) allows a time gate of a few nanoseconds, a small fraction of the 25ns between LHC bunch crossings, to

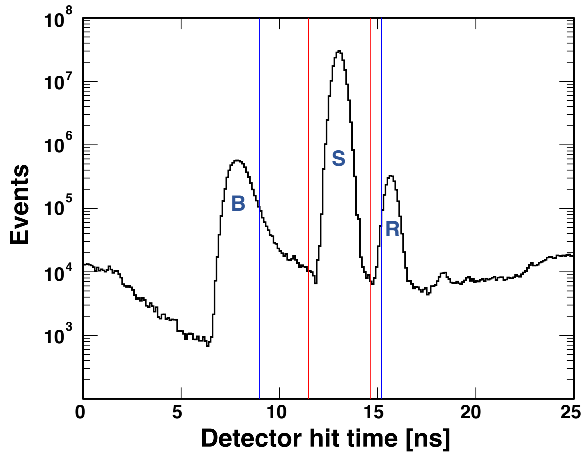

Figure 3. Simulated arrival time of photons in RICH 1 accumulated over many proton-proton collisions. The peak labeled S corresponds to the Cherenkov signal, B is background mainly from particles crossing directly the photon detectors and R is photons with additional reflections. The red band shows a 3.125 ns window around the signal and the blue band a 6.25 ns window.

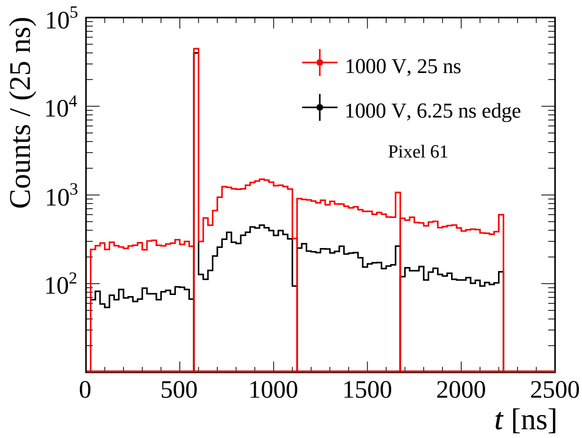

Figure 4. Photon hits accumulated on one MaPMT pixel during tests with a particle beam. When a 6.25 ns gate is applied the continuous background is reduced by a factor of three to four while the signal peak remains unaffected.

collect all the signal while rejecting out-of-time background. In addition to the LHC background the time gate also reduces dark counts and out of time after-pulses from the MaPMTs. This was studied during particle beam tests at the CERN SPS with a 180 GeV/c hadron beam. The results can be seen in figure 4 where the signal-to-noise ratio improves by a factor of three to four using a 6.25 ns time gate.

The time gate is applied using the FPGA on the front-end digital board. The programmable logic in the FPGA is adapted to sample the CLARO signals at 320 MHz using the deserialiser embedded in every input-output logic block as seen in figure 5. The byte from the deserialiser is used to address a lookup table and the bit at this memory location is presented at the output on each 40 MHz clock edge. The lookup table can therefore be configured to detect specific input patterns and to apply the time gate around the signal from the CLARO chip. Figure 3 shows the 3.125 and 6.25 ns time gates in red and blue respectively. The alignment of the time gate with respect to the signal peak can be calibrated by shifting the sampling clock phase with respect to the LHC bunch crossing clock. The overall time resolution of the electronic readout chain may require the wider time gate of 6.25 ns to be used to achieve the best particle identification performance.

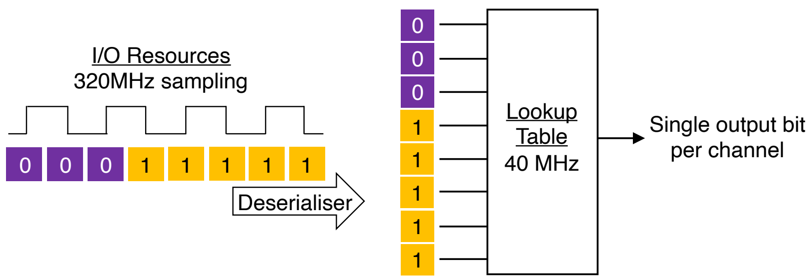

Figure 5. Schematic diagram of the implementation of the timing gate. The output of the CLARO ASIC (not shown) is sampled at 320 MHz, detecting the arrival of the signal with a time window of 3.125 ns and resulting in eight samples every 25 ns. The 8-bit byte is compared to a configurable lookup table for validity before being presented at the FPGA output.

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4 Cherenkov angle resolution

There are three main contributions to the Cherenkov angle resolution of a typical RICH detector: detection point error (pixel size), emission point error and chromatic error. With the new RICH 1 geometry and the new photon detectors (with higher quantum efficiency in the green and blue) we expect significant improvements. Table 1 shows a comparison between the current and the upgraded RICH detectors (where the upgraded values come from simulation). The Cherenkov angle resolution of RICH 1 shows an improvement by of factor of two, and is a major contribution to the improved performance of the system.

Table 1. The main components of the Cherenkov angle resolution. The pixel size error for the HPDs has an extra contribution from the Point Spread Function (PSF) at the anode, while the bigger MaPMTs in RICH 2 have a larger pixel error.

Contributions to resolution (in mrad)	RICH 1-2015 current HPD	RICH 1-upgrade MaPMT	RICH 2-2015 current HPD	RICH 2-upgrade MaPMT
Chromatic	0.84	0.58	0.48	0.31
Pixel	0.60	0.44	0.19	0.19 (large = 0.4)
Point spread function	0.86		0.29	
Emission Point	0.76	0.37	0.27	0.27
Overall	1.60 →	0.78	0.65 →	0.45

5 Quality assurance and current status

Reliability is an essential requirement of the photon detectors and various electronic components, so a number of test centres have been set up to test and characterise individual components as well as larger assembled pieces, up to fully assembled photon detector columns.

All the 3072 MaPMTs plus spares have been tested and characterised with their main characteristics (average gain, gain variations between pixels and quantum efficiency for a small sample) compared with the data from the manufacturer. There is generally very good agreement between measurements. The granularity of the high voltage distribution implies the same HV for 16 small MaPMTs. Characterisation of the MaPMTs allows grouping on the photon detector plane according to gain and thus achieves uniformity of response.

All of the CLARO ASICs (more than 30,000) have been tested individually for basic functionality and tested again after mounting on the front-end boards. MaPMTs and front-end electronics have been assembled into elementary cells and about half (enough to fully populate RICH 2) have been tested and delivered to CERN. The digital boards have the GBT functionality on plug-in modules allowing flexibility in case of radiation damage. All of the GBT modules have been tested and about half the full boards have been successfully tested.

6 Summary

More than 10 years of ideas, design and production of detector components are coming to fruition for the LHCb RICH Upgrade. All of the required elements from photon detectors to mirror supports

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have been produced or are in the final stages of manufacturing. In particular enough MaPMTs and read-out electronics have been fully assembled in photon detector columns to fully populate RICH 2. The RICH project is on track to have fully commissioned RICH detectors in 2020.

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