



Full Length Article

The upgrade II of the LHCb RICH System[☆]C. Gotti[✉]*, on behalf of the LHCb RICH Collaboration

INFN Milano Bicocca, Piazza della Scienza 3, 20126, Milano, Italy



ARTICLE INFO

Keywords:

RICH detectors
Particle identification
High luminosity LHC
Photon detectors
Fast electronics

ABSTRACT

The Ring Imaging Cherenkov (RICH) detectors of the LHCb experiment have provided charged hadron identification over a wide momentum range since the start of data taking at the LHC. After a first major upgrade currently operating in LHC Run 3, the LHCb experiment foresees a second, more ambitious “Upgrade II” to operate at five to seven times higher instantaneous luminosity starting from Run 5. The RICH system will face unprecedented challenges in terms of photon rates, radiation, timing requirements and mechanical constraints, while aiming to maintain the same or better particle identification (PID) performance. This paper provides an overview of the LHCb RICH Upgrade II programme, summarizing the main detector requirements and the ongoing R&D activities on photon detectors, cooling, optics and fast electronics.

1. Introduction

The LHCb experiment has successfully operated during the LHC Run 1 and 2 (2010–2018), collecting about 9 fb^{-1} of integrated luminosity [1]. A first major upgrade was deployed during the LHC Long Shutdown 2 (2019–2022) [2]. Data taking with the upgraded detector started in 2022, and the data collected by September 2025 corresponds to an integrated luminosity of 16 fb^{-1} , aiming at 50 fb^{-1} by the end of Run 4. A second major upgrade of the detector (“Upgrade II”) is planned for installation during the LHC Long Shutdown 4 (LS4) to take data in the mid-2030s until the end of the LHC era [3–5]. It will operate at a maximum luminosity of $1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with the aim to accumulate a sample of 300 fb^{-1} of pp collision data. Fig. 1 shows the planned evolution of LHCb, with its peak and integrated luminosities. While the overall layout of the Upgrade II detector, shown in Fig. 2, will not differ significantly from the current one, the harsher operating conditions will require a substantial redesign of most detector subsystems. This redesign will include the RICH detectors, which provide the experiment’s crucial hadron PID capability.

2. The LHCb RICH system and upgrade II challenges

The LHCb RICH detectors are designed to cover a wide momentum range [6,7]. RICH1, upstream of the magnet, uses a C_4F_{10} radiator to cover momenta in the range 2–40 GeV/c with an acceptance angle of 25–300 mrad. RICH2, downstream, uses CF_4 to cover a momentum range of 15–100 GeV/c with an acceptance angle of 15–120 mrad.

Currently (LHC Run 3) the photon detectors are multi-anode photo-multiplier tubes (MaPMTs) with pixel size of $3 \times 3 \text{ mm}^2$ in RICH1 and the central regions of RICH2, and $6 \times 6 \text{ mm}^2$ in the periphery of RICH2. Peak photon rates in the central regions of RICH1 range up to $10^8 \text{ photons/s/cm}^2$, corresponding to a pixel occupancy of 30% [8]. The MaPMTs are read out with an amplifier-discriminator ASIC named CLARO, located close to the MaPMTs in the so-called “Elementary Cell” [9,10]. The close proximity of the front-end ASICs to the MaPMTs ensures that noise and cross-talk are minimized. Fast binary signals corresponding to photon hits on each pixel are driven to a FPGA on the digital board named PDMDB, where they are packaged and transmitted off-detector. The entire opto-electronics chain can withstand a 40 MHz event rate with no dead time and no spillover.

With the $5\times - 7.5\times$ increase in peak luminosity foreseen for Upgrade II, the occupancy in the central regions of RICH1 would exceed 100%, making them inoperable. Maintaining a satisfactory PID performance in Upgrade II requires first and foremost a way to mitigate the occupancy in RICH1, and keep it close to the present peak level of 30%. One way to achieve this will be to increase the focusing length and the radii of the spherical mirrors. Given the limited space available and the essentially unchanged detector envelope, a 50% increase in focusing length is considered feasible, which mitigates the occupancy by a factor two. The other handle to reduce occupancy will be to use photon detectors with smaller pixels.

In the peripheral regions of RICH1 and the entire RICH2, occupancy is not as critical. As a consequence, a modification of the RICH2 optics is not strictly mandatory, at least from the point of view of detector

[☆] This article is part of a Special issue entitled: ‘RICH2025’ published in Nuclear Inst. and Methods in Physics Research, A.

* Corresponding author.

E-mail address: claudio.gotti@mib.infn.it.

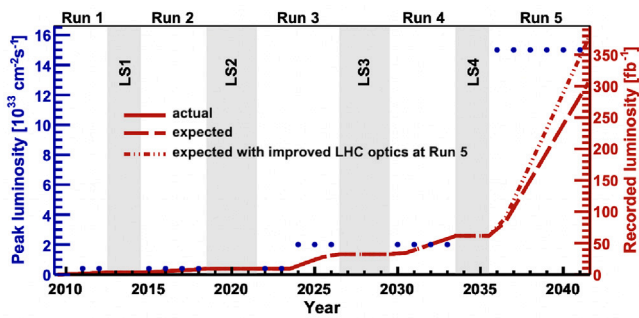


Fig. 1. LHCb peak and integrated luminosities until the end of the LHC era.

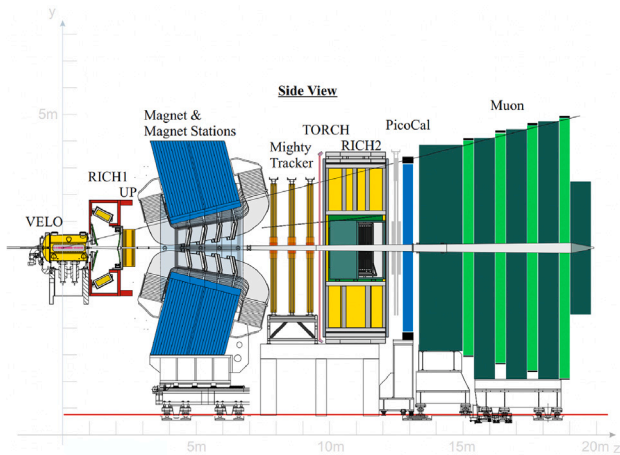


Fig. 2. Layout of the LHCb detector in Upgrade II.

operability. However, maintaining good PID capability with a much higher track density calls for better Cherenkov angle resolution, which is contributed by the chromatic error (due to dispersion), the emission point error (due to optical aberrations), and the pixel error (due to pixel size). The overall current simulated values are 0.82 mrad for RICH1, with a photon yield of 62 photons for saturated tracks, and 0.50 mrad for RICH2, with a photon yield of 39 photons for saturated tracks [5]. A breakdown is shown in Fig. 4 as “MaPMT (Run 3)”. The observed values for Run 3 are still being evaluated, but they are not far from the above estimates [8]. In order to improve the resolution in Upgrade II, all three contributions must be addressed, while at the same time maximizing the photon yield. The chromatic error can be reduced by using photon detectors with peak sensitivity at longer wavelength, the emission point error by improving the optical layout, and the pixel error by reducing the pixel size.

Time-tagging of single Cherenkov photons at the 100 ps level will also be fundamental in separating signals coming from different tracks, to mitigate pile-up and improve event reconstruction. The time of arrival of Cherenkov photons at the photodetector plane can in fact be predicted to a precision of tens of ps [11]. This feature has not been used in Run 3, where just a 6.25 ns time gate is applied for each 25 ns bunch crossing, but may be used to improve PID performance in Upgrade II, and possibly already in Run 4. The ultimate limit to time resolution will then be determined by the photon detector. Two scenarios have been compared when estimating the PID in Upgrade II, with photons binned at 300 ps and 150 ps. The latter showed a significantly better PID performance, particularly at low momenta [5]. None of these two scenarios seem achievable with current MaPMTs, which have a time resolution closer to 400 ps FWHM [12], hence faster photon detectors need to be considered.

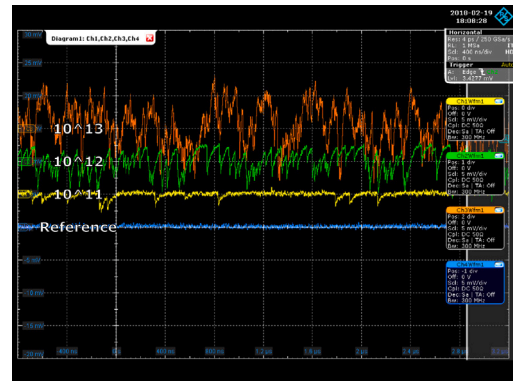


Fig. 3. Dark noise of irradiated $1.3 \times 1.3 \text{ mm}^2$ Hamamatsu S13360-1350CS SiPMs at $-30 \text{ }^\circ\text{C}$. The blue curve is a reference device (non irradiated). The orange curve is a device irradiated to 10^{13} cm^{-2} 1-MeV equivalent neutrons, which is still a factor three below the current estimates for the LHCb Upgrade II.

Source: Taken from [16].

3. Key R&D areas

3.1. Photon detectors

The need to mitigate the higher occupancy with smaller pixels, as mandatory in the central regions of RICH1, prevents the use of standard dynode-based MaPMTs, which do not exist with pixels below $3 \times 3 \text{ mm}^2$. For these reasons they are only considered as a possible backup option for cost reduction in the peripheral regions of RICH1 and RICH2.

Two alternative and established technologies are under study for Upgrade II: silicon photomultipliers (SiPM) and microchannel-plate photomultiplier tubes (MCP-PMT). Compared with MaPMTs, both offer a better time resolution and a pixel size which can be adjusted as needed, although for very small pixels cross-talk would need to be carefully assessed, especially for MCP-PMTs. A direct comparison sees SiPMs offering higher quantum efficiency, while MCP-PMTs give better time resolution. However, none can be easily used in the harsh conditions of the LHCb Upgrade II.

SiPMs suffer severely from radiation, as the non-ionizing energy loss caused by high hadron fluences damages the silicon lattice, dramatically increasing the rate of dark counts and causing other detrimental effects. A dedicated FLUKA simulation [13,14] has estimated that the 1-MeV-equivalent neutron fluence by the end of Run 5 will range up to $3 \times 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$, without considering shielding and with no safety factor. Radiation damage can be at least partially alleviated by cooling. Fig. 3 shows the effect of neutron irradiation up to $10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$ to the dark count rate of $1.3 \times 1.3 \text{ mm}^2$ SiPMs (Hamamatsu S13360-1350CS) cooled to $-30 \text{ }^\circ\text{C}$, where single-photon sensitivity is clearly lost. Given the high fluence, the cooling requirements may range down to liquid nitrogen temperatures [15]. Periodic annealing at high temperature will also be essential, as it may help in mitigating the dark count rate (DCR) by approximately an order of magnitude [16], although the feasibility of heating up the entire photodetector planes of the RICH detectors in LHCb, for instance during technical stops, is still under study. Periodic replacement of SiPMs may also be an option, although difficult and costly. R&D is ongoing with Hamamatsu Photonics and Fondazione Bruno Kessler to develop devices that are best suited for these challenging conditions. This activity has a clear synergy with the work being done for the LHCb SciFi detector and with the goals of the DRD4 collaboration.

MCP-PMTs do not fear radiation, and in particular neutron fluence, as much as SiPMs. They would not require cooling or annealing, and provide an overall better time resolution than SiPMs. Their quantum

Configuration		Overall	Chromatic	Emission pt.	Pixel	Yield
		[mrad]	[mrad]	[mrad]	[mrad]	
RICH1	MaPMT (Run 3)	0.82	0.59	0.38	0.46	62
	SiPM	0.51	0.28	0.37	0.22	65
	SiPM & geometry	0.38	0.28	0.13	0.22	52
RICH2	MaPMT (Run 3)	0.50	0.33	0.37	0.20	39
	SiPM	0.42	0.19	0.36	0.10	33
	SiPM & geometry	0.22	0.19	0.05	0.10	25

Fig. 4. Expected changes in Cherenkov angle resolution and photon yield from the current system, to one with SiPMs (different QE and smaller pixels) and one where also the optical layout is changed (“geometry”).
Source: Taken from [5].

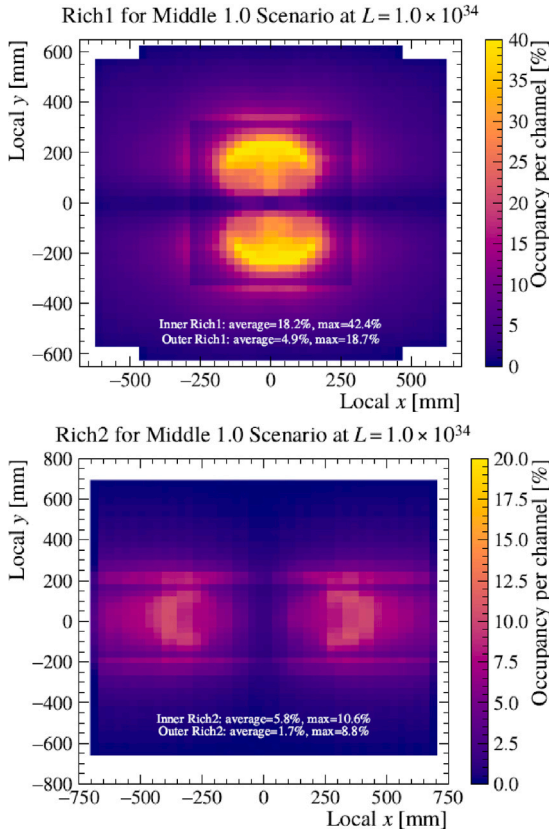


Fig. 5. Simulated occupancy on the RICH1 (top) and RICH2 (bottom) detector planes for one of the target Upgrade II scenarios.
Source: Taken from [5].

efficiency is lower than SiPMs, especially at longer wavelengths where the chromatic dispersion is lower. Their main drawback, however, is that they saturate at rates above 10^7 photons/s/cm², one or two orders of magnitude below the highest photon rates foreseen in Upgrade II in the central regions of RICH1. The development of high-rate picosecond photodetectors (HRPPDs), an evolution of the LAPPD devices developed by Incom, Inc. for application at the future Electron-Ion Collider (EIC), shows promising results [17], although the increase in rate capability compared to state-of-the-art MCPs is not yet fully characterized.

Compared with other R&D efforts, the time scale of the LHCb RICH Upgrade II is relatively short. Based on present available technology, and despite the challenges involved, SiPMs operated at very low temperature (around 100 K) seem to be the only existing photon detectors that may satisfy the requirements, at least for the central regions of RICH1 where the signal rate is highest.

3.2. Cooling concepts

Despite the challenging cooling requirements, SiPMs are now considered the baseline photon detectors, and the feasibility of operating the RICH photon detector planes down to cryogenic temperature is under study. A vacuum cryostat concept with a thick transparent window separating the photon detector plane from the gas radiator volume is under evaluation. A small-scale demonstrator has been built and will be tested in laboratory and beam tests at CERN in 2026 [18]. The front-end electronics could still be in vacuum but at a higher temperature, connected to the SiPMs with flex circuits, or will need to be placed at cryogenic temperature close to the SiPMs. An alternative approach explores local cooling of the SiPMs to -60 °C or -80 °C using ceramic PCBs with integrated micro-channels for coolant circulation. The possibility of increasing the temperature of the SiPMs to 100 – 150 °C to anneal radiation damage during LHC technical stops is also being considered. This cooling (and heating) system is one of the major design challenges of the LHCb RICH Upgrade II.

3.3. Optics optimization

The redesign of the RICH optics for Upgrade II aims to increase the focusing length in a tightly constrained detector envelope. This is vital in the central regions of RICH1 to mitigate the increase in occupancy. In the rest of the detector it is a means to reduce optical aberrations, hence improving the emission point error and pixel error contributions to the Cherenkov angle resolution, while maximizing the photon yield. The concept involves repositioning the flat mirrors within the detector acceptance and increasing the radius of curvature of the spherical mirrors, within the constraints of the existing detector envelope. The improved layout shows a significant improvement in the overall angular resolution. Together with smaller photon detector pixels, it gives an overall improvement to Cherenkov angle resolution by about a factor two compared to the present (Run 3) optical layout [5]. Fig. 4 summarizes the current estimates for variations in resolution and photon yield by the use of SiPM alone, with smaller pixels and a quantum efficiency peaked at longer wavelength compared to MaPMTs (450 nm instead of 300 nm), and by also changing the layout of the mirrors (referred to as “geometry”).

Fig. 5 shows the simulated occupancy of the RICH detectors in one of the Upgrade II luminosity scenarios ($5\times$ compared with Run 3). Increasing the focal length by 1.4 and reducing the pixels size to 2×2 mm² results in a peak occupancy of 40%, pushing the upper limit that can be sustained for efficient high rate single photon counting.

An alternative layout is under study, with split mirrors on each side of the RICH detectors to separate the high- and low- occupancy regions [19]. Further increase of focusing length and further reduction of pixel size to 1.4×1.4 mm² are also being considered.

3.4. Timing and electronics

Simulations show that time-tagging the Cherenkov photons at the 100 ps level will be highly beneficial to recover PID performance at high pile-up. The front-end electronics of Upgrade II will need to make full use of the time resolution offered by the photon detectors. The leading candidate is the FastRICH ASIC, which evolved from the FastIC ASIC, designed in 65 nm CMOS technology [20]. It features a front-end stage that can accept signals of positive or negative polarity, it includes a time-to-digital converter with 25-ps bins, and it was made radiation tolerant by the use of triple modular redundancy in the digital part [21]. The first prototype has already been manufactured and is under test since mid-2025 in the laboratory and on beam with positive results. The early development of the front-end ASIC is a key part of the LS3 Enhancement programme [22,23].

3.5. Calibration and alignment

A dedicated calibration, alignment and monitoring system is under development, based on Rayleigh scattering of pulsed laser light parallel to the photon detector plane. It will provide a uniform and time-resolved illumination of the detector, enabling precise monitoring and in-situ calibration. Deployment is planned during LS3 as part of the LS3 Enhancement program [24].

3.6. Alternative radiators

Fluorinated gases C_4F_{10} and CF_4 , while highly effective as Cherenkov radiators in the LHCb RICH detectors due to their excellent optical transparency and refractive index properties, are potent greenhouse gases with high global warming potentials (GWP). R&D to find green alternatives are underway, and the possibility of replacing CF_4 with CO_2 in RICH2 is being evaluated, in synergy with the DRD4 activities [25].

4. Outlook and conclusions

The Upgrade II of the LHCb RICH system represents one of the most demanding RICH detector projects ever undertaken. It will require significant advances in photon detection technology, cooling, optics and fast electronics. The programme benefits from strong synergies with one of the CERN Detector R&D collaborations (DRD4), leveraging developments in fast and radiation-hard photodetectors and cryogenic operation. Ongoing R&D activities across all fronts are converging toward a detector design capable of maintaining high PID performance under the extreme conditions foreseen in the LHCb Upgrade II.

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.

References

- [1] The LHCb Collaboration, The LHCb Detector at the LHC, *J. Instrum.* 3 (2008) S08005, <http://dx.doi.org/10.1088/1748-0221/3/08/S08005>.
- [2] The LHCb Collaboration, The LHCb Upgrade I, *J. Instrum.* 19 (2024) P05065, <http://dx.doi.org/10.1088/1748-0221/19/05/P05065>.
- [3] LHCb Collaboration, Expression of Interest for a Phase-II LHCb Upgrade, 2017, CERN-LHCC-2017-003. URL: <https://cds.cern.ch/record/2244311>.
- [4] LHCb Collaboration, Framework TDR for the LHCb Upgrade II, 2021, CERN-LHCC-2021-012. URL: <https://cds.cern.ch/record/2776420>.
- [5] LHCb Collaboration, LHCb Upgrade II Scoping Document, 2024, CERN-LHCC-2024-010. URL: <https://cds.cern.ch/record/2903094>.
- [6] LHCb Collaboration, LHCb RICH : Technical Design Report, 2000, CERN-LHCC-2000-037. URL: <https://cds.cern.ch/record/494263>.
- [7] R. Calabrese, et al., Performance of the LHCb RICH detectors during LHC Run 2, *J. Instrum.* 17 (2022) P07013, <http://dx.doi.org/10.1088/1748-0221/17/07/P07013>.
- [8] G. Cavallero, The LHCb RICH detectors: operations and performance, 2025, Talk at RICH2025.
- [9] M. Baszczyk, et al., CLARO: an ASIC for high rate single photon counting with multi-anode photomultipliers, *J. Instrum.* 12 (2017) P08019, <http://dx.doi.org/10.1088/1748-0221/12/08/P08019>.
- [10] M. Baszczyk, et al., Test of the photon detection system for the LHCb RICH Upgrade in a charged particle beam, *J. Instrum.* 12 (2017) P01012, <http://dx.doi.org/10.1088/1748-0221/12/01/P01012>.
- [11] A. Upadhyay, Primary vertex time reconstruction using LHCb RICH detectors, 2025, Talk at RICH2025.
- [12] M. Calvi, et al., Single photon time resolution of photodetectors at high rate: Hamamatsu R13742 MaPMT and R10754 MCP-PMT, *J. Instrum.* 15 (2020) P10031, <http://dx.doi.org/10.1088/1748-0221/15/10/P10031>.
- [13] C. Ahdida, et al., New Capabilities of the FLUKA Multi-Purpose Code, *Front. Phys.* 9 (2022) 788253, <http://dx.doi.org/10.3389/fphy.2021.788253>.
- [14] G. Battistoni, et al., Overview of the FLUKA code, *Ann. Nucl. Energy* 82 (2015) 10–18, <http://dx.doi.org/10.1016/j.anucene.2014.11.007>.
- [15] M. Guarise, Characterization of SiPMs for the LHCb RICH Detectors Upgrade-II, 2025, Poster at RICH2025.
- [16] M. Calvi, et al., Single photon detection with SiPMs irradiated up to 10^{14} cm⁻² 1-MeV-equivalent neutron fluence, *Nucl. Instrum. Methods Phys. Res. Sect. A* 922 (2019) 243–249, <http://dx.doi.org/10.1016/j.nima.2019.01.013>.
- [17] D. Foulds-Holt, Large Area Picosecond Photodetector for the Upgrade II of the LHCb RICH, 2025, Poster at RICH2025.
- [18] L. Malentacca, A cryogenic RICH detector demonstrator for SiPM operation with integrated flex-PCB electronics, 2025, Poster at RICH2025.
- [19] E. Spadaro Norella, Optimized optical design of the LHCb RICH detectors for Upgrade-II, 2025, Poster at RICH2025.
- [20] S. Gomez, et al., FastIC: A Highly Configurable ASIC for Fast Timing Applications, in: 2021 IEEE Nuclear Science Symposium and Medical Imaging Conference, NSS/MIC, 2021, <http://dx.doi.org/10.1109/NSS/MIC44867.2021.9875546>.
- [21] F. Keizer, The FastRICH ASIC for next-generation RICH detectors, 2025, Talk at RICH2025.
- [22] LHCb Collaboration, LHCb Particle Identification Enhancement Technical Design Report, 2023, CERN-LHCC-2023-005. URL: <https://cds.cern.ch/record/2866493>.
- [23] V. Placinta, The LS3 Enhancement of the RICH detectors, 2025, Poster at RICH2025.
- [24] R. Cardinale, CalAliMon: In-Situ Rayleigh-Scattering based Calibration Alignment and Monitoring system for the future LHCb RICH upgrades, 2025, Poster at RICH2025.
- [25] G. Hallewell, Controlling refractive index and reducing the Global Warming Potential of Cerenkov gas radiators: a challenge in the era of diminishing fluorocarbon availability, *Nucl. Instrum. Methods Phys. Res. Sect. A* 1055 (2023) 168493, <http://dx.doi.org/10.1016/j.nima.2023.168493>.