Nuclear Instruments and Methods in Physics Research A 1058 (2024) 168824

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

The LHCb RICH upgrade for the high luminosity LHC era

S.A. Wotton *, On behalf of the LHCb RICH Collaboration

Cavendish Laboratory, University of Cambridge, Cambridge, UK

ARTICLE INFO

Keywords:
LHCb
RICH
LHC
Particle identification

ABSTRACT

The hadron particle identification provided by the RICH system in LHCb over a momentum range of 2.6–100 GeV/c has been a key element of the success of the experiment and will remain equally important for Upgrade II. With luminosities expected up to 7.5 times those expected for Upgrade I and 75 times those realised in the past, maintaining the current excellent particle identification performance demands a substantial improvement in the precision of the measurements of the space and time coordinates of the photons detected in the RICH. It will require a readout strategy with high-resolution timing information and making significant improvements in the resolution of the reconstructed Cherenkov angle.

1. Introduction

The proposed high luminosity upgrade of the CERN Large Hadron Collider provides an opportunity for the LHCb experiment to significantly extend the physics program [1] but presents technical challenges in handling the resulting much higher detector occupancies. In order to fully exploit the future physics program, the current excellent particle identification performance will need to be maintained under these more challenging conditions. The target luminosity for LHCb in Upgrade II is $1.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ which represents a factor 7.5 increase compared to the current situation. With this luminosity, the 1 MeV equivalent neutron dose in the region of the RICH 1 photon sensors is estimated to be 10^{13} cm^{-2} and the total ionising dose over the detector lifetime is estimated to be 5 kGy. The LHCb Ring Imaging Cherenkov (RICH) system consists of two RICH detectors, RICH 1 for the lower momentum range uses C_4F_{10} as radiator, RICH 2 for higher momenta uses CF_4. These detectors will continue to be a crucial element of the particle identification system and improvements will be required in several areas. In these proceedings I will discuss some of the ideas and developments under consideration for the proposed upgrade. Further details on the LHCb detector proposals for Upgrade II can be found in Ref. [2].

2. Photon detection spatial resolution

In the current LHCb RICH detector the chromatic error, emission point error and pixel error contribute approximately equally to the overall Cherenkov angle resolution. Therefore in order to significantly improve the resolution all three contributions must be reduced. The choice of photon sensor, Cherenkov radiator and optical properties of the detector all play an important role.

The chromatic error is driven by the wavelength dependence of radiator refractive index, photon sensor response, mirror reflectivity and absorption in the photon transmission media. In this respect, silicon photomultipliers (SiPMs) would have a significant advantage over multi-anode photomultipliers (MaPMTs) as the photon sensor since their sensitivity typically peaks in the green part of the spectrum where the variation of refractive index of the gaseous C_4F_{10} radiator is smaller. An estimated factor five reduction in the chromatic error could be achieved for RICH 1 with this change.

The tilt of the spherical mirror allows the photon sensors and front-end electronics to be located outside the detector acceptance but generates an error due to the unknown emission points of the photons within the radiator. For Upgrade II, modified optical geometries are therefore under consideration with one possibility being a reduction of the mirror tilt from 316 mrad to 258 mrad. This will require the secondary flat mirrors to move inside the detector acceptance resulting in more material inside the acceptance and reduced radiator path length. The use of light-weight materials for the mirrors and their supports will be required. An estimated factor three reduction in the emission point error in RICH 1 can be achieved with this new layout with only a modest reduction in photon yield.

In order that the pixel size does not then dominate the overall error it will be necessary to replace the existing photon sensors. For MaPMTs it is likely that current technology is already close to the limit of the smallest pixel size at a little below 3 mm. On the other hand, SiPM arrays are readily available with pixel sizes as small as 1 mm. Smaller pixels

* Corresponding author.
E-mail address: wotton@hep.phy.cam.ac.uk.

https://doi.org/10.1016/j.nima.2023.168824
Received 12 January 2023; Accepted 23 October 2023
Available online 7 November 2023

may also be achievable with new sensor developments such as large area picosecond photon detectors (LAPPDs) that have customisable anode structures although the technology in this area is not yet as well developed.

Table 1 Compares the photon yield and estimated contributions to the overall angular resolution for the current 2.88 mm pixel MaPMT configuration against the example of replacing the MaPMTs with 1 mm pixel SiPMs with and without adjustments to the optical layout. With these improvements, the overall angular resolution is improved by almost a factor 4.

3. Choice of photon sensor

The spatial resolution is not the only consideration in the choice of photon sensor. The channel occupancy also has a significant impact on the detector design. Experience has shown that good particle identification (PID) performance can be achieved with channel occupancies up to about 30 %. However, estimates of the peak occupancy in the current configuration already approach this value in some regions of the image plane. Naive scaling to high luminosity conditions where an additional factor 7.5 luminosity is expected would indicate that the channel occupancy would then exceed 100 %. The use of sensors with smaller pixel size in the highest occupancy regions is therefore likely to be required in order to reduce the channel occupancy although other techniques such as front-end electronics with multiple thresholds are also under consideration. The use of a sensor with immunity to magnetic fields would allow the removal of the magnetic shielding currently required for the operation of the MaPMTs and this may allow more flexibility to modify the detector layout and achieve additional gains. The additional benefits and technical challenges of using photon sensors with excellent timing resolution are discussed in Section 4.

There are a few candidate photon sensors that come close to meeting the LHCb requirements for Upgrade II. Of these, the SiPM and LAPPD are perhaps the current favourites. Some of the most relevant sensor attributes are summarised in Table 2 in comparison with those of MaPMTs. The most important disadvantage of SiPMs is their large dark count rate and the increase of dark count rate under irradiation. Nevertheless, these devices remain under consideration due to their numerous other advantages and mitigations such as cryogenic operation, high temperature annealing and periodic replacement of irradiated sensors are being explored. LAPPDs are a type of vacuum tube photon sensor based on micro-channel plate (MCP) technology which share the excellent timing properties of MCPs. They also have the attractive features of large area coverage per device combined with a customisable external capacitatively-coupled anode structure and rectangular geometry. On the other hand, currently available LAPPDs have not yet been demonstrated with pixel sizes close to 1 mm and their spectral sensitivity is not ideally matched to the LHCb requirements. Gain ageing under high photo-current conditions has been a limiting factor, however, recent improvements in their gain ageing characteristics, for example by the use of atomic layer deposition coatings, have been observed [3]. A detailed evaluation of the candidate sensor properties is being performed in the collaborating institutes [4] and at the CERN beam facilities.

Table 1
Contributions to the total angular resolution for RICH 1 and RICH 2.

Configuration	Overall [mrad]	Chromatic [mrad]	Emission point [mrad]	Pixel [mrad]	Yield
RICH 1					
MaPMT	0.80	0.52	0.36	0.50	63
SiPM	0.40	0.11	0.36	0.15	47
SiPM + geom	0.22	0.11	0.12	0.15	34
RICH 2					
MaPMT	0.50	0.34	0.32	0.22	34
SiPM + geom	0.13	0.10	0.05	0.07	20–30

Table 2
Comparison of photon sensor attributes.

	MaPMT	SiPM	MCP/LAPPD
Time resolution, σ_t [ps]	150	60	30
Pixel size [mm]	≥2.5	≥1	Custom (R&D)
Quantum Efficiency	>35 % at 350 nm	>45 % at 460 nm	20–30 % at 350 nm
Dark count rate [Hz mm^{-2}]	1	10^5–10^7	1
Typical operating voltage	1 kV	<100 V	1 kV
B-field limit	<5 mT	Insensitive	<2 T
Radiation tolerance	Entrance window	Lattice defects	Entrance window
Gain ageing limits	$I_{anode} < 100$ μA	N/A	10 C cm^{-2}

4. Time-resolved single photon readout

The PID performance of the LHCb RICH detectors deteriorates as the detector occupancy increases because detected photons from all sources form a background to those associated to a given particle. Furthermore, the multiple interactions occurring within the same LHC bunch crossing are currently not resolved in the read out and therefore contribute to the occupancy seen by the PID algorithm. Under present luminosity conditions, the use of spatial information is sufficient to reliably associate photons with particles and achieve excellent PID performance. Under high-luminosity LHC conditions, the number of interactions per bunch crossing will increase and spatial information alone will no longer be sufficient. However, individual interactions within the same bunch crossing are distributed in time as well as space (see Figs. 1 and 2) so the implementation of time-resolved read-out will allow the photons from unrelated interactions to be removed from consideration, resulting in an effective reduction in occupancy. Simulations show that sufficiently precise knowledge of the photon time of arrival on the RICH image plane can be used to recover the excellent PID performance [5]. Fig. 3 illustrates the potential gain in PID performance and motivates the use of sensors and front-end electronics able to resolve photons separated by less than 100 ps. The challenge for the upgrade of the LHCb RICH is therefore to identify a photon sensor and design a front-end read-out electronics system capable of the high precision time-stamping of individual photons and transporting the high volume of data from the detector.

The development of a new front-end ASIC, FastRICH [6], is already in progress with the aim of replacing the existing readout electronics during 2026–2028 while keeping the existing MaPMT photon sensors [7]. Although the transit time spread of the MaPMTs will ultimately limit the time resolution at this stage, it will nevertheless allow a fully compatible readout chain to be validated well in advance of Upgrade II and provide an incremental improvement in the PID performance. It has been shown in simulation that the RICH data alone will be sufficient to provide a primary vertex reference time even before the upgrade of other subdetectors to add timing capabilities. The ultimate time resolution would then be achieved with the replacement of the photon sensors and the upgrade of the LHCb tracking detectors during

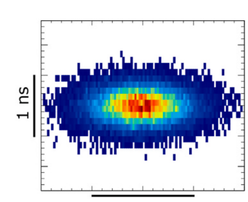

Fig. 1. Simulated distribution of proton-proton interaction time (σ_t = 200 ps) and position (σ_z = 60 mm) within an LHC bunch-crossing averaged over many bunch crossings.

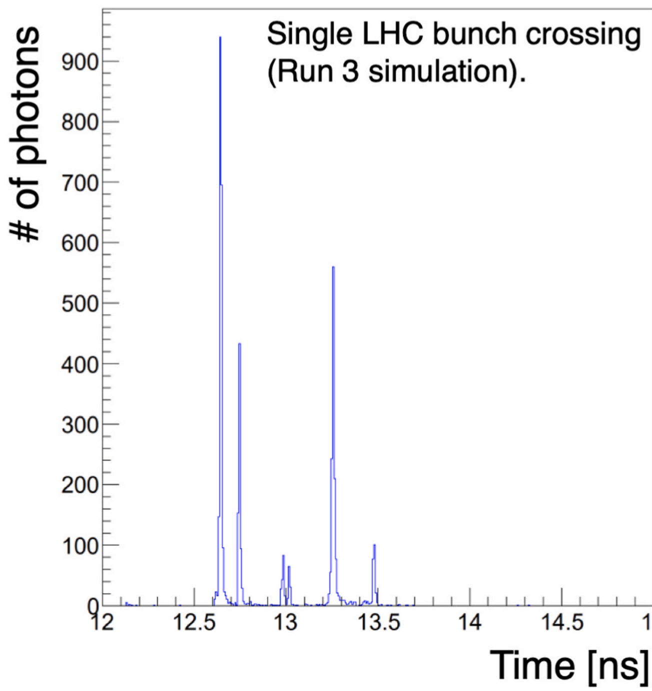

Fig. 2. Simulated time of arrival of all signal photons within a single typical bunch crossing. The peaks correspond to photons coming from the same proton-proton interaction.

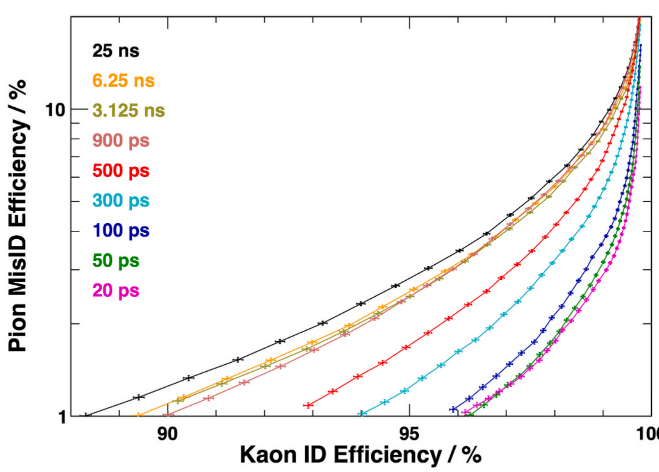

Fig. 3. Kaon identification efficiency vs. pion misidentification probability for hypothetical photon sensors having different time resolutions. Best performance corresponds to the bottom right of the plot where efficiency to correctly identify a kaon is maximum and the probability to misidentify the kaon as a pion is minimum.

2033–2034.

The required bandwidth to read out the data with high detector occupancy will be compounded by the additional bits required to encode the photon time-of arrival. The expected 30 % peak pixel occupancy corresponds to a hit rate of about 10 MHz. Assuming each hit requires 8 bits to encode the time, this corresponds to 80 Mbit/s per pixel before adding protocol and synchronisation headers. The FastRICH ASIC will have 16 analogue input channels and 4 digital serial output links operating at up to 1280 Mbit/s which is sufficient to sustain the peak average occupancy. However, fluctuations in the instantaneous hit rate must also be taken into consideration and a detailed evaluation of the impact of these is ongoing. In order to achieve the small number of bits to encode the time with the required precision and range, the FastRICH ASIC will employ constant fraction discrimination. This will avoid the need to use additional bits to encode the time-over-threshold and also reduce the required range by removing the contribution due to time-walk effects. Furthermore, the FastRICH ASIC will implement a configurable time gate that will be used to digitally select only those signal hits that fall within the physically allowed time interval. This is significantly smaller than the 25 ns cycle time and so reduces the amount of transmitted data due to the rejection of non-signal photons. The small pixel size will result in a high channel density and the proximity of the electronics to the temperature-sensitive photon sensors imposes the requirement that the FastRICH must have low power dissipation. Nevertheless, the thermo-mechanical engineering design will present significant challenges given the small available volume which must also accommodate the components required for the data transmission. The FastRICH is designed to be directly coupled to the CERN lpGBT transceiver which transmits the data off-detector over long-distance fibre-optic cables at 10 Gbit/s and which distributes also the signals needed to synchronise and configure the front-end electronics.

5. Outlook

The LHCb RICH collaboration is actively engaged in a program of developments towards the proposed upgrade to exploit the high luminosity LHC era. In these proceedings I have selected a few of the challenges that lie ahead with emphasis on the optical layout, choice of photon sensor and implementation of time-resolved readout. A strategy for the instrumentation of the photon sensors is becoming well-developed and, in addition to this, there are many other areas in active development such as: designs for possible cryogenic operation with SiPMs; studies of new aerogel radiators and novel radiators based on meta-materials; new designs for light detection including new mirror geometries and micro-lensing, the use of green gases as radiators and coolants; and new reconstruction methods using novel architectures and algorithms.

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.

Acknowledgements

The author acknowledges the support of the UK Science and Technology Facilities Council and the funding agencies of the RICH collaboration.

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