An Overview of the Status of the LHCb RICH Detectors

N. Harnew
On behalf of the LHCb RICH Group
University of Oxford, Department of Physics, Oxford OX1 3RH, UK

Abstract

The LHCb experiment will make precision measurements of CP violation and rare b-hadron decays. Efficient particle identification with high purity over a wide momentum range is vital to these aims. The experiment employs two ring-imaging Cherenkov (RICH) detectors with three radiators, silica aerogel, C_4F_{10} and CF_4, to cover the momentum range from around 1 to 100 GeV/c. The RICH system employs a number of innovative techniques, both in hardware and software. A total of 484 custom-built pixel Hybrid Photon Detectors (HPDs) will be used to measure the spatial positions of Cherenkov photons with wavelengths in the range 200 to 600 nm, covering an active area of around 3.3 m^2. The production of the HPDs has now been completed and the tube quality, including the photo-cathode quantum efficiency, far exceeds expectations. The installation of RICH 1 is almost complete; RICH 2 has been installed and aligned, and commissioning is almost complete. Reconstruction studies incorporating realistic backgrounds indicate excellent kaon efficiencies of around 97% and pion misidentification probabilities of around 6%, averaged over the full momentum range. selection. This paper provides a general overview of the status of the LHCb RICH project, with emphasis on the readiness for LHC start-up and for physics.

Key words: LHCb experiment, RICH detectors, Hybrid Photon Detectors, Aerogel, Carbon-fibre mirrors
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1. Introduction

The LHCb experiment [1] will make precision measurements of CP violation and rare decays of b hadrons at the Large Hadron Collider (LHC). The LHCb detector, shown in Fig. 1, is a forward spectrometer. This design is optimized to accept the decay products of $\bar{b}$ and b hadrons, which are preferentially produced with a strong angular correlation in the forward-backward directions.

Particle identification is essential to separate pions from kaons in selected B meson decays. Two ring-imaging Cherenkov (RICH) detectors perform π/K separation from around 1 to $\sim$100 GeV/c [2]. The polar angular acceptance of the upstream RICH 1 detector, in the spectrometer bending plane, is 25 to 300 mrad, while that for the downstream RICH 2 is 15 to 120 mrad. The properties of

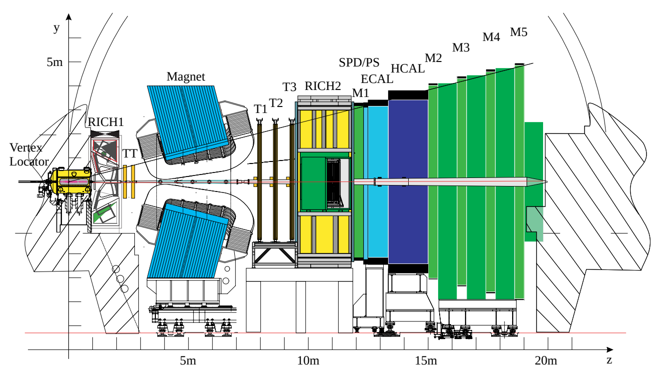

Fig. 1. A schematic of the LHCb detector.

Email address: n.harnew1@physics.ox.ac.uk (N. Harnew).

Table 1
Properties of the RICH detectors and the radiators.

	RICH 1		RICH 2
Property / Radiator	Aerogel	C_4F_{10}	CF_4
Radiator length (mm)	50	950	1800
Refractive index	1.03	1.0014	1.0005
Detected p.e./track	5.3	24	18
Momentum range (GeV/c)	∼1–10	<70	<100

the RICH detectors are summarized in Table 1.

Pixel Hybrid Photon Detectors (HPDs) have been developed to detect and reconstruct the Cherenkov rings [3]. A total of 484 HPDs cover the ∼3.3 m^2 total photon detection area, consisting of 196 HPDs in RICH 1 and 288 in RICH 2.

2. The RICH 1 detector

A schematic of the RICH 1 detector is shown in Fig. 2. The optical arrangement has symmetry about the horizontal plane, with two sets of spherical and plane mirrors focusing the Cherenkov photons onto a pair of photon detector arrays. Two radiator materials are employed: aerogel and C_4F_{10} gas.

The RICH 1 detector has a number of novel features. To minimize material in the spectrometer, the LHC beryllium beam-pipe defines the detector inner acceptance. The beam-pipe directly seals to the 2 mm RICH 1 entrance window, which also serves as the Al exit window to the LHCb vertex locator (VELO). The beam-pipe also seals to the exit window, manufactured from poly-methyl-methacrylimide (PMMI) foam sandwiched inside carbon-fibre skins.

Four carbon-fibre spherical mirrors, with radii of curvature 2700 mm, focus the Cherenkov photons [4][5]. The mirrors are located inside the LHCb spectrometer acceptance and hence must present a low fraction of a radiation length, $\sim 1.5\%$ of X_0, which is essential to minimize secondary interactions. A total of 16 planar mirror segments, located outside the spectrometer acceptance, then reflect the Cherenkov photons onto two detection planes, arranged above and below the beampipe. Each detection plane contains seven columns each of 14 HPDs.

A total of 16 silica aerogel tiles has been procured for use in RICH 1 for the identification of low momentum particles between 1 to 10 GeV/c. The LHCb aerogel has unprecedented optical quality [6][7][8] and large size, up to $200 \times 200 \times 5\,\mathrm{mm}^3$. The aerogel

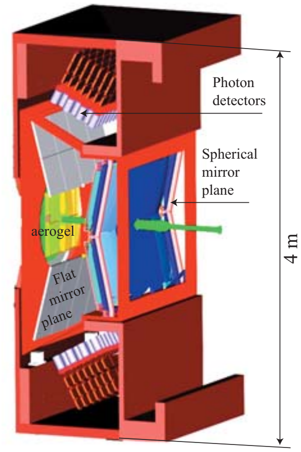

Fig. 2. A schematic of the RICH 1 detector.

has a nominal refractive index of 1.030 at 400 nm, a clarity coefficient of 0.005 μm^4/cm and a refractive index homogeneity of $\sigma(n-1)/(n-1) < 1\%$ [8]. The aerogel is tolerant towards irradiation and shows no change in transparency after an accumulated fluence of protons, neutrons and γ's up to the doses expected in LHCb.

The installation of the components of RICH 1 is almost complete. The external and internal structures and seals to the beampipe are in place and all mirrors have been installed. The RICH 1 detector will be commissioned early in 2008.

3. The RICH 2 detector

A schematic of the RICH 2 detector is shown in Fig. 3. The optical arrangement has symmetry about the vertical plane. As in RICH 1, two sets of spherical and plane mirrors focus the Cherenkov photons onto two photon detector arrays. The radiator material employed is CF_4 gas.

The RICH 2 superstructure has a carbon-fibre-skinned polymeric foam entrance window and aluminium-skinned foam-core exit window. The detector contains 56 spherical mirror segments made from 6 mm thin glass substrates, and 40 flat mirror segments. Since the detector is located downstream of the tracking system and immediately upstream of the calorimeter system, a higher material budget for the optical system can be tolerated.

The RICH 2 detector was transported from the main CERN site to the LHCb experimental cavern in November 2005. The mirrors were aligned

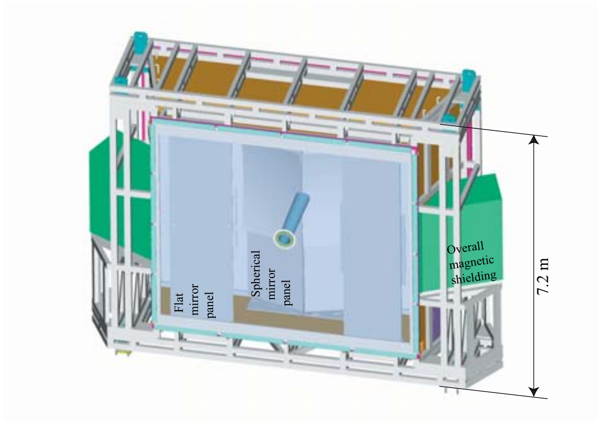

Fig. 3. A schematic of the RICH 2 detector.

to a precision of $\sim$150 μrad before the move; afterwards the mirror movement was estimated to be $\sim$100 μrad. This is to be compared with the expected RICH 2 Cherenkov angle resolution of $\sim$700 μrad, hence there was no need to re-align the mirrors *in situ*. Commissioning of the RICH 2 detector is now well underway [9].

4. The Hybrid Photon Detectors

The pixel Hybrid Photon Detector, shown in Fig. 4, will detect Cherenkov photons in the wavelength range 200–600 nm [3] and has been developed in collaboration with industry . The HPD consists of a vacuum tube with a 7 mm-thick quartz entry window which has a sensitive diameter of 72 mm. An S20 photo-cathode is deposited on the inner surface of the window. The photo-electrons are accelerated by a cross-focusing electrostatic field onto an anode, using a tetrode electron optics and a demagnification factor of five. The anode is a pixel silicon sensor to which is bump-bonded an LHCBPIX1 readout chip [10], operating at the LHC frequency of 40 MHz. At the operating voltage of 20 kV, the photo-electrons produce about 5000 electron-hole pairs in the silicon sensor. A total of 32×32 channels per HPD are read out, giving an effective granularity of $2.5 \times 2.5\,\mathrm{mm}^2$ at the photocathode.

The production of the HPDs involved seven companies and production sites, with Photonis-DEP [11] as the lead partner. The HPDs were qualified at two Photon Detector Test Facilities to provide quality assurance before they were accepted for use in LHCb [12]. The average quantum efficiencies (QEs) of the full sample of 550 production HPDs are shown

Fig. 4. A photograph of the pixel Hybrid Photon Detector with a 10 cm scale.

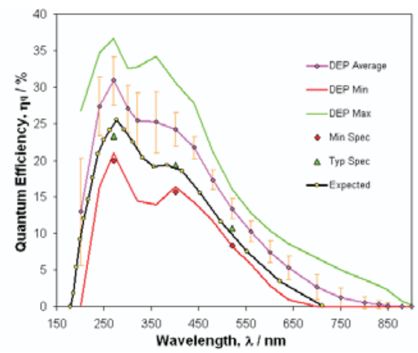

Fig. 5. The average measured quantum efficiencies of 550 HPDs as a function of wavelength. The performance is compared to the specification and the expected values from the pre-series HPDs.

as a function of photon wavelength in Fig. 5 and also compared to the expected performance from the pre-series HPDs. The average QE is better than 30% at 270 nm, also showing a $\sim$ 25% improvement over the pre-series sample. Of the HPDs delivered from Photonis-DEP, 98% passed the selection criteria.

5. RICH commissioning and calibration

The first phase of commissioning was performed in test beams at the CERN PS and SPS [13][14]. Three columns of the RICH 2 detector, equipped with final HPDs, electonics and data acquisition, were read out at the LHC frequency of 40 MHz in an 80 GeV/c pion beam with a 25 ns bunch structure. Beam particles entered the vessel through a thin aluminum foil and passed through a $\sim$1m length of either N_2 or C_4F_{10} radiator gas. Cherenkov light was focused by a parabolic mirror onto the photodetector plane.

All HPDs were arranged in columns with their

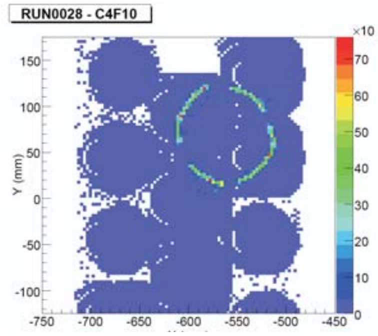

Fig. 6. Ring images on four HPDs from an 80 GeV/c pion beam and C_4F_{10} radiator, integrated over $\sim$ 50k events.

ancillary front-end electronics. Dedicated Low Voltage and High Voltage cards powered the HPDs for which an advanced and dedicated LHCb RICH Detector Control System (DCS) was in place [15]. The so-called "Level-0" boards [16] read out the HPDs in pairs and passed triggered data via 100 m of optical fibre to the off-detector processor board, the so-called "UKL1" board. The UKL1 board receives and zero-suppresses the data and transmits them onwards to the central LHCb data acquisition system.

Ring images, integrated over $\sim$50k events, are shown in Fig. 6 for a 80 GeV/c pion run with a C_4F_{10} radiator. Very few hits are seen outside the ring, indicating a very low level of noise. The distribution of the number of measured photo-electrons (p.e.) per event was fitted with a Poisson distribution, modified for multiple pixel hits and charge-sharing. The data and the fit are shown for a typical data run in Fig. 7, showing excellent agreement. The LHCb requirements for photon yield have thus been verified.

Commissioning *in situ* started with the RICH 2 detector [9]. All HPD columns have been operated

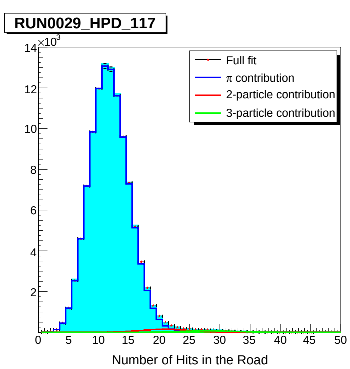

Fig. 7. The number of p.e. observed per event for a C_4F_{10} run. The Poisson fit to these data is also shown (solid line), together with background contributions.

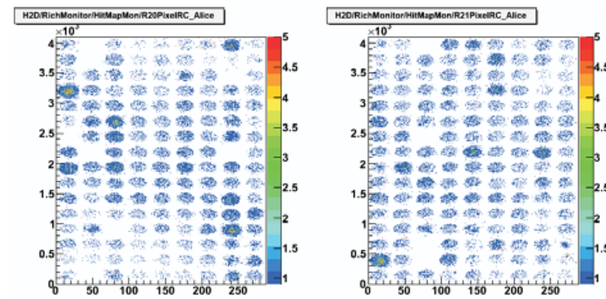

Fig. 8. A hit map of all RICH 2 HPD pixels in response to a laser source of photons (10 kV applied to the HPDs).

at 20 kV, and this has now become a routine and safe task. Ten out of 288 HPDs (3%) have failed, and these tubes have been disconnected and will be replaced. Figure 8 shows a hit map of all HPD pixels of RICH 2 in response to a laser source of photons. RICH 2 is currently being commissioned with the rest of the LHCb sub-detectors and RICH 1 will follow early in 2008.

RICH calibration procedures are being prepared [17]. The HPDs must operate in a magnetic fringe field, up to a maximum of 2.4 mT in regions of RICH 1. Correction factors must therefore be applied for electron image rotations due to the E×B effects within the tubes. Studies show that for a locally-shielded HPD in a 3 mT field there is no loss of active HPD area due to these image distortions [18]. Calibration and alignment procedures will also be performed using measured tracks in data events. Techniques to be employed will be real-time refractive index monitoring and determination of Cherenkov angle resolution from saturated ($\beta \approx 1$) isolated rings. Calibration of the particle identification performance will be achieved using uniquely identified pions and kaons from D* decays [19].

6. RICH performance studies

The LHCb RICH performance has been extensively simulated in the GEANT4 Monte Carlo framework including realistic tracking and effects of all known background processes [20]. A global pattern recognition and ring-fitting approach has been adopted, with simultaneous assignment of rings to tracks in RICH 1 and RICH 2 [21]. Distributions of hit pixels on the HPD planes in RICH 1 are shown for a typical B event in Fig. 9. Rings characteristic of the two radiators can be clearly seen.

The expected RICH performance from the Monte Carlo simulation and global reconstruction is shown

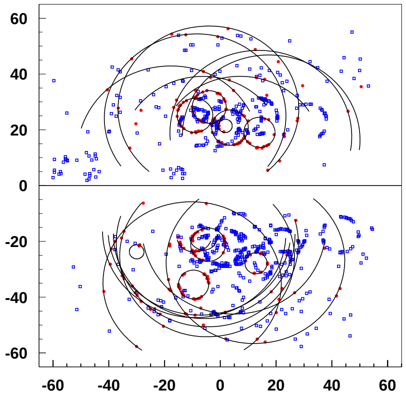

Fig. 9. Distributions of hit HPD pixels on the HPD planes of RICH 1 in a simulated event, with the global fits to the Cherenkov rings which have associated tracks superimposed. Scales are in cm.

in Fig. 10, including all known background processes. The figure shows the efficiency for kaons identified as "heavy" particles (K,p) and the probability for pions misidentified as heavy, as a function of momentum, for those tracks which traverse the full LHCb spectrometer. The average efficiency, integrated over the full spectrum, is 97%. The average probability for pion misidentification over the same momentum range is $\sim$6%.

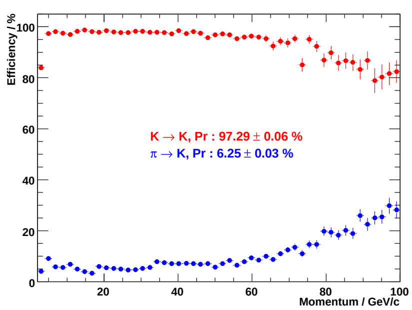

Fig. 10. The kaon efficiency and pion misidentification probability (in %) as a function of momentum for the "heavy" particle (K,p) assignment.

7. Summary and conclusions

The LHCb experiment employs two RICH detectors to provide particle identification over the momentum range 1–100 GeV/c, which is essential for the B-physics programme. The RICH 1 detector utilizes innovative carbon-fibre mirror and aerogel technology and its installation is almost complete. RICH 2 has been installed and aligned and is being commissioned *in situ*. The 484 Hybrid Photon Detectors have all been fully qualified and have excellent photon sensitivity. Cherenkov light yields and resolutions have been verified in beam tests and the simulated particle identification performance meets all LHCb requirements. The LHCb RICH system will be ready for first LHC collisions in 2008.

References

[1] The LHCb Collaboration, LHCb Re-Optimized Detector Design and Performance Technical Design Report, CERN/LHCC 2003-030, LHCb TDR9, September 2003.

[2] The LHCb Collaboration, LHCb RICH Technical Design Report, CERN/LHCC 2000-037, LHCb TDR3, 7 September 2000.

[3] T. Gys *et al.*, Nucl. Instr. and Meth. **A465** (2001) 240.

[4] R. C. Romeo *et al.*, Proc. SPIE, 6273, 62730S (2006).

[5] F. Metlica, "Development of light-weight spherical mirrors for RICH detectors", these proceedings.

[6] T. Bellunato *et al.*, Nucl. Instr. and Meth. **A519** (2004) 493.

[7] D. Perego, "Ageing Tests and Recovery Procedures of Silica Aerogel", these proceedings.

[8] T. Bellunato, "Refractive index of silica aerogel: uniformity and dispersion law", these proceedings.

[9] C. D'Ambrosio, "Commissioning of the LHCb RICH Detectors", these proceedings.

[10] K. Wyllie *et al.*, Nucl. Instr. and Meth. **A530** (2004) 82.

[11] Photonis/DEP, Dwazziewegen 2, Roden 9300 AB, Netherlands.

[12] S. Eisenhardt, "Production and Tests of Hybrid Photon Detectors for the LHCb RICH Detectors", these proceedings.

[13] M. Adinolfi *et al.*, Nucl Inst. and Meth. **A574** (2007) 39.

[14] S. Brisbane, "The operation of the LHCb RICH photon detection system in a charged particle test beam", these proceedings.

[15] M. Sannino, LHCb RICH Detector Control and High Voltage Systems", these proceedings.

[16] M.Adinolfi *et al.*, Nucl Inst. and Meth. **A572** (2007) 689.

[17] A. Papanestis, "The calibration and alignment of the LHCb RICH system", these proceedings.

[18] G. Aglieri Rinella *et al.* Nucl. Instr. and Meth. **A553** (2005) 120.

[19] R. Muresan, Nucl. Phys. Proc. Suppl. **170** (2007) 237.

[20] C. Buszello, "LHCb RICH Pattern Recognition and Particle Identification Performance", these proceedings.

[21] R. Forty, Nucl. Instr. and Meth. **A433** (1999) 257.