Hybrid photon detectors for the LHCb RICH

Stephan Eisenhardt

University of Edinburgh, School of Physics, Mayfield Road, Edinburgh EH9 3JZ, UK

On behalf of the LHCb RICH Collaboration

Available online 24 May 2006

Abstract

The LHCb Ring Imaging Cherenkov (RICH) counters use the pixel Hybrid Photon Detector (HPD) as a photo-sensitive device. Photo-electrons are produced in a semi-transparent multi-alkali photo-cathode (S20) and are accelerated by a voltage of 20 kV onto a pixelated silicon anode. The anode is bump-bonded to the LHCbPIX1 pixel readout chip which amplifies and digitises the anode signals at the LHC speed of 40 MHz. Using a demagnification of five, the effective pixel size at the HPD window is $2.5 \times 2.5 \text{ mm}^2$. Over the course of 18 months, 550 HPDs will undergo a quality-assurance programme to verify the specifications and to characterise the tubes. The tested parameters include the threshold and noise behaviour of the chip, the response to light emitting diode (LED) light, the demagnification of the electron optics, the leakage current and the depletion of the silicon sensor, the quality of the vacuum, the signal efficiency and the dark count rate. Results of tests of the first nine HPDs of the final design are presented and compared to the specifications.

© 2006 Elsevier B.V. All rights reserved.

PACS: 85.60.Ha; 85.60.Dw; 29.40.Ka

Keywords: Hybrid photon detector; Silicon pixel sensor; Ring Imaging Cherenkov (RICH) counter

1. Introduction

The LHCb experiment [1,2] is a single-arm spectrometer for precision measurements of CP-violation in the decay of B-mesons produced in 14 TeV pp-collisions at the LHC collider. This requires an excellent separation of π - and K-mesons over the momentum range of 2–100 GeV. This is achieved by a combination of two Ring Imaging Cherenkov (RICH) counters [2,3]. RICH 1 employs Aerogel and C_4F_{10} as radiators and is situated upstream of the LHCb bending magnet. RICH 2 employs CF_4 and is positioned downstream of the magnet. RICH 1 covers the phase space of lower momenta and larger scattering angles ranging from 2 to 60 GeV and 25 to 250(300) mrad in the non-bending (bending) plane, respectively. It operates in the fringe field of the bending magnet. RICH 2 covers the higher momenta and smaller scattering angles ranging from 17 to 100 GeV and 15 to 100(120) mrad, respectively.

When fast charged particles traverse the radiators of the RICH detectors they emit Cherenkov photons. In the LHCb detectors these are collected and focused by spherical mirrors into ring images at the photo-detector plane. The spherical mirrors are tilted to reflect the photons onto secondary plane mirrors which allow placement of the photo-detectors outside the acceptance of the spectrometer. The single photons are recorded with sufficient spatial resolution to measure the diameter of the Cherenkov ring images and hence the velocity of the charged particles which emitted the photons.

The chosen photon detector for the LHCb RICHes is the Hybrid Photon Detector (HPD). The HPDs cover an area of $\sim 3.0 \text{ m}^2$ and are sensitive to single photons in the wavelength range of 200–600 nm. They have typical quantum efficiencies (QEs) of $\sim 25\%$ at 270 nm. The photo-detectors also provide a granularity of $2.5 \times 2.5 \text{ mm}^2$ and an active area fraction of $\sim 65\%$. This corresponds to about 500 000 electronic channels which have to be read out at the LHCb speed of 40 MHz. The HPDs also have to be radiation tolerant up to $\sim 3 \text{ kRad}$ per year.

E-mail address: S.Eisenhardt@ed.ac.uk.

2. Hybrid photon detectors

The HPD [4] is shown schematically in Fig. 1. A vacuum photon detector tube is equipped with a pixelated silicon sensor (Si-sensor) and a readout chip as anode.

The photo-tube uses a 7 mm thick quartz entry window with an S20 photo-cathode deposited on its inner surface. It has a sensitive diameter of 72 mm. The typical integrated QE is $\int QE dE > 0.7 \text{ eV}$. The photo-electrons are accelerated by a cross-focusing electrostatic field onto the anode, using a tetrode electron optics and a de-magnification factor of five. At the operating voltage of 20 kV, a photo-electron is accelerated to produce about 5000 electron-hole pairs in the Si-sensor. About 18% of the photo-electrons scatter back into the vacuum of the HPD and only partially deposit their energy. Approximately half of the back-scattered photo-electrons are lost as their signals do not exceed the threshold.

A photograph of the pixel HPD is shown in Fig. 2. The outer dimensions of the vacuum tube are defined by the diameter of the window seal of 83 mm and a height of 120 mm from the base to the apex of the window.

The Si-sensor is pixelated in an array of 256×32 pixels of size $62.5 \times 500 \mu\text{m}$. This small size has a small capacitance which results in a low noise for each pixel. The sensor is bump bonded to the LHCPIX1 pixel chip [5] which provides a preamplifier, a shaper and a discriminator circuit for each pixel, giving a binary readout. The sensor and readout chip are encapsulated inside the vacuum tube. The LHCb readout mode makes use of a fast eight-fold logic OR after the discriminator to form a 32×32 array of super-pixels of effective size of $500 \times 500 \mu\text{m}$. With the de-magnification factor of five, these super-pixels translate to a size of $2.5 \times 2.5 \text{ mm}$ at the photo-detector entrance window.

The production of the HPDs is a logistical challenge involving seven companies and production sites, coordinated by the LHCb RICH group. The most crucial steps are the bump bonding of the Si-detector to the readout

Fig. 1. Schematic of a hybrid photon detector.

Fig. 2. Photograph of a hybrid photon detector with 10 cm scale.

chip using a high-temperature solder (VTT, Finland), the packaging of this assembly into the ceramic carrier (HCM, France) and the photo-tube production (Photonis-DEP, Netherlands) which involves a bake-out at 300°C . The success and the yield of each production step are checked by dedicated tests. The HPDs then are subject to a series of tests to verify the specifications and to provide a final quality assurance before they are accepted for usage in LHCb. The RICH detectors will be equipped with 484 HPDs in total.

3. Photo-detector tests

A total of 550 HPDs, which includes spares, will be procured and characterised over the course of 18 months. The delivery and test rate will be 30 HPDs per month. To cope with this production rate, two Photon Detector Test Facilities (PDTFs) have been set up at the Universities of Edinburgh and Glasgow. Four fully equipped test stations have been installed, i.e. two at each site, with the test procedures automated wherever possible. One test station per site is used for the tests, mandatory for the quality assurance, at the rate of one HPD per work day per site. The second station is used for a more time-consuming additional characterisation carried out on about 10% of the produced HPDs, as well as providing redundancy in case of station failure.

Each HPD has to pass the mandatory test programme. The readout chip is scanned with charge injection pulses to demonstrate that the global discriminator threshold and the pixel noise are below 2000 e^- and 250 e^- , respectively. This ensures a minimum separation of 12σ between signal and threshold. For the nine HPDs the separation exceeds 20σ . To obtain the characteristic $I-V$ curve of the silicon sensor, the leakage current is scanned against the bias voltage. This tests whether the leakage current is sufficiently low and the sensor is operating in the over-depleted

regime. The response of the HPD to pulsed light produced by a LED at a wavelength of 470 nm is recorded. This determines the number of pixels that are sensitive to light, tests the integrity of the electrostatic field, and tests whether the sensor is properly positioned inside the vacuum envelope. The quality of the vacuum of the tube is deducted from the rate of delayed ion feedback signals, described below. The rate of dark counts is observed for a time after ramping the 20 kV supply voltage to show that the rate is sufficiently small and that operation is stable.

Two additional characterisations are performed on a sub-sample of the HPDs. The photo-electron detection efficiency, defined as the probability for the detection of a photo-electron after it has been converted at the photo-cathode, is determined. Secondly, the QE of the photo-cathode is measured.

The specifications characterising the performance of the HPD are summarised in Table 2, together with typical results obtained from the first nine pre-series HPDs of the final design. These results are discussed below.

4. Test results

Fig. 3 displays the response of a HPD to charge injection in the range from 0 to 2000 e[−] for a given global threshold. The approximate range of responses from individual pixels is illustrated by three selected pixels together with the response of the HPD averaged over 8192 pixels. The response curve for each pixel is fitted to find the 50% point and the slope at this point. Using these results, the average threshold and the noise of the readout chip are calculated.

Fig. 3. HPD response to charge injection between 0 and 2000 e[−] for a given global threshold; displayed are the response of three individual pixels and the average over the full HPD.

Fig. 4 displays such a distribution of thresholds of all pixels of a single HPD with an average of 1134 e[−]. The RMS of 84.8 e[−] is achieved without the 3-bit threshold adjustment of the individual pixels. The charge injection scan allows for a calculation of the optimum settings of this adjustment to further reduce the spread of thresholds across the readout chip. For the nine pre-series HPDs the threshold and noise values were found in the range of 1100–1300 e[−] and 150–180 e[−], respectively. This is well below the specified limits of 2000 e[−] and 250 e[−].

The HPDs are exposed to short LED light pulses with a width of about 15 ns and an intensity of 2–3 photo-electrons per event. The response of an HPD is shown in Fig. 5. The outer circular boundary is the image of the sensitive area of the photo-cathode projected on the sensor array. A slight mis-alignment of the assembly in the HPD, characteristic for the pre-series run, is visible. The de-magnification is as expected. The ring structures observed are caused from internal total reflection of light from a ring-shaped Al-coating connecting the photo-cathode to the electrode on the inside of the quartz window. This coating will be shadowed in the final design. Neglecting this effect, the response is uniform over the photo-cathode surface. Only six pixels in the sensitive area show no response to the light. Eight of the nine pre-series HPDs show response to light for more than 99% of the pixels in the active area. In one of the HPDs a full column was missing, believed to be a detached wire bond inside the tube. This reduces the number of responding pixels to 94.8%, but only just misses the specification of at least 95% active pixels.

Ion feedback occurs when a photo-electron ionises a residual gas atom in the vacuum tube. The ion drifts back to the photo-cathode and releases secondary photo-electrons. At the Si-sensor the secondaries form clusters of hits. The delay of these clusters relative to the primary photo-electron is governed by the drift time of the ion. Fig. 6 presents the measured rate of delayed ion feedback

Fig. 4. Threshold distribution of all pixels of a single HPD before the adjustment of the individual 3-bit thresholds.

Fig. 5. Response of an HPD to pulsed LED light of 470 nm at a rate of ≈ 3 photo-electrons per pulse.

Fig. 7. Response of an HPD in a high statistic dark count run (five million events).

Fig. 6. Rate of ion feedback events relative to primary photo-electron of a ~ 15 ns wide LED pulse.

clusters relative to the primary photo-electrons. The distribution peaks at a delay of 200 ns and becomes less significant from 300 ns onwards. The peak rate is 1.5×10^{-4} of the photo-electron signal. The typical rate for the pre-series HPDs is 10^{-3} , compared to the specification of less than 10^{-2} .

The number of dark counts has been specified to be less than 5 kHz/cm² to limit the number of background hits in the detector. The main sources of dark counts are thermionic electron emission at the photo-cathode, electrostatic field emission and the resulting ion feedback. Fig. 7 displays the response of an HPD in a dark count run (i.e. with no LED) of five million events. A few large ion feedback clusters are visible. The observed photo-electrons

Fig. 8. Evolution of the rate of dark counts for an HPD after ramping up to 20 kV supply voltage.

correspond to the lowest dark count rate of 0.03 kHz/cm² observed in the pre-series HPDs. The largest value measured is 3.0 kHz/cm². This is from the tube with the highest QE in the red part of the spectrum, causing it to be most sensitive to thermionic emission. Fig. 8 exhibits how the dark count rate evolves over time after ramping to the operating voltage of 20 kV. An initial rise is caused by the heating up of the cathode. The rate then settles to the stable state in about 90 min.

The response of an HPD to LED light, measured for a scan of the high voltage in the range from 0 to 20 kV, is shown in Fig. 9. The two thin curves represent the number of raw pixel hits per event measured for scans with decreasing and increasing high voltage, respectively. The

Fig. 9. Response of an HPD versus the applied high voltage. The square data points represent the number of photo-electrons from the cluster algorithm.

Fig. 10. Response of an HPD versus the applied bias voltage. The square data points represent the number of photo-electrons from the cluster algorithm.

square data points are the corresponding number of reconstructed photo-electrons per event as computed by an event-by-event clustering algorithm which combines neighbouring hits from charge sharing and ion feedback clusters. The thick curves represent the number of photo-electrons as expected from the Poisson distribution of hits for each measurement. They perfectly match the result of the clustering algorithm. The onset of the sensitivity is at 5 kV corresponding to a global threshold of $\sim 1250 e^-$. At 10 kV, 90% of the maximum sensitivity is reached and charge sharing between neighbouring pixels becomes visible. The slow rise of the sensitivity of photo-electrons above 10 kV is attributed to the rising probability to measure signals from back-scattered photo-electrons which only deposit a fraction of their energy. The operating voltage of 20 kV is well within the region of stable operation.

The response of the HPDs to LED light is measured by ramping the bias voltage in the range of 0–90 V, shown in Fig. 10. The sensor is fully depleted at ~ 50 V. The operating point is set at 80 V, into the over-depleted region. The shape of this curve is very sensitive to the timing of the light with respect to the data acquisition clock.

The typical leakage current of the Si-sensor has to be restricted to about $1 \mu A$ at 80 V bias supply to limit heating and noise. Fig. 11 presents the results for the pre-series HPDs. Eight of the pre-series HPDs satisfy the limit. For one HPD a leakage current of $4.3 \mu A$ was measured at 80 V bias supply. This tube operates well in all other respects and therefore still is suitable for operation in the LHCb RICH detectors.

Fig. 11. The leakage current across the anode versus the applied bias voltage for the pre-series HPDs.

The QEs of the photo-cathodes of the nine pre-series HPDs were determined using a xenon lamp and a monochromator as light source. The current of emitted photo-electrons was measured using a picoampere meter with the photo-cathode negatively biased and the electrodes and the anode at ground potential. To calibrate the HPD current each measurement was repeated with a photo-diode with known QE. The results are shown in Fig. 12. The specification points are given as crosses and listed in Table 1. The shapes of the curves are defined by the cut-off of the quartz window at 200 nm and the properties of the S20 photo-cathode leading to the variations in the near

Fig. 12. Quantum efficiency of nine pre-series HPDs.

Table 1
Specification of the quantum efficiency

Wavelength (nm)	Minimum QE (%)	Typical QE (%)
270	20.0	23.3
400	15.7	19.3
520	8.3	10.7

UV and the visible region. For eight HPDs, the specifications are well exceeded. Only one HPD (3_1) slightly misses the minimum specification in the UV, in turn it provides the strongest efficiency in the red. This tube will be used in the outer region of RICH 1 where red photons from the aerogel radiator are abundant. Whilst the wavelength dependence of the QE for each tube is measured and supplied by the manufacturer, a sample will be measured at the test stations using a calibrated photo-diode as reference.

To determine the photo-electron detection efficiency, the spectrum of charge pulses on the bias supply line can be measured. These ‘backpulses’ result from recharging of the Si-sensor after the collection of photo-electrons occurred on the anode. The backpulse method integrates over all pixels and therefore it is affected by the large capacitance of the full sensor chip, hence single-photon peaks are not easily discernable. Fig. 13 shows such a spectrum recorded with a multi-channel analyser, where one can distinguish the contributions of single photo-electrons. A fit to determine the Poissonian weights of the contributions determines an average of 2.3 photo-electrons per event in this sample.

In the binary readout, signal loss occurs for small signals below threshold and when the signal is discriminated late due to time-walk. The photo-electron detection efficiency is then the ratio of the number of photo-electrons observed

Fig. 13. A typical backpulse spectrum of signals of photo-electrons hitting the anode, measured on the bias supply line.

Table 2

Main specifications of the HPDs together with the typical results obtained from the first nine pre-series tubes

Item	Spec.	Typ. results
<i>Mandatory tests</i>		
Threshold	$< 2000 e^-$	$< 1200 e^-$
Noise	$< 250 e^-$	$< 160 e^-$
Pixel response (%)	> 95	> 99
Ion feedback rate rel. to signal	$< 10^{-2}$	$< 10^{-3}$
Dark count rate (kHz/cm ²)	< 5	0.03–3.0
Leakage current typ. at 80 V bias (μA)	1	< 1
<i>Additional characterisation</i>		
Photo-el. det. eff. (%)	Typ. 85	79–89

through the binary readout and the number measured with the backpulse method. Due to the poor signal-to-noise ratio intrinsic to the backpulse method, the photo-electron detection efficiency can only be measured for those pre-series HPDs with a sufficiently low leakage current, i.e. with low-noise conditions. For the pre-series HPDs, efficiencies in the range of 79–89% were measured. This compares well to the requirement of typically 85%.

The results for the nine pre-series HPDs are summarised in Table 2. Apart from a few exceptions the performance matches or exceeds the design specifications. Even in those cases where the specifications are missed, the HPDs are still suitable for use in the LHCb RICH detectors.

5. Conclusions

The tests have shown that the HPDs meet the requirements of the LHCb RICH detectors. The performance of the pre-series HPDs gives good expectations for a high yield of production HPDs within specifications. The production of the 550 HPDs has started and robust testing procedures are in place. The first batch of tested HPDs

ready for installation in the RICH 2 detector of LHCb is expected in January 2006.

References

- [1] A large hadron collider beauty experiment for precision measurements of CP violation and rare decays, LHCb Technical Proposal, LHCC 98/04, LHCC/P4, February 1998.
- [2] LHCb – reoptimized detector design and performance, Technical Design Report, CERN/LHCC 2003-030, LHCb TDR 9, 9 September 2003.
- [3] S. Amato et al., LHCb – RICH Technical Design Report, CERN/LHCC/2000-0037, LHCb TDR 3, September 2000.
- [4] M. Alemi, et al., Nucl. Instr. and Meth. A 449 (2000) 48.
- [5] K. Wyllie et al., A pixel readout chip for tracking at ALICE and particle identification at LHCb, Proceedings of the Fifth Workshop on LHC Electronics, Snowmass, CO, USA, 20–24 September 1999, CERN/LHCC/99-33.