Nuclear Instruments and Methods in Physics Research A 639 (2011) 94–98

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Operating the Hybrid Photon Detectors in the LHCb RICH counters

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ARTICLE INFO

Available online 21 November 2010

Keywords:
Ring Imaging Cherenkov detectors
Hybrid Photon Detectors
LHCb

ABSTRACT

Results are presented on the commissioning and operation of Hybrid Photon Detectors used in the Ring Imaging Cherenkov detectors of LHCb. Cherenkov photons from proton–proton interactions at a centre-of-mass energy of 7 TeV have been recorded. An explanation is given of the steps that have been taken to achieve these results.

1. Introduction

Photon detection in the Ring Imaging CHerenkov (RICH) detectors at LHCb is accomplished through the use of Hybrid Photon Detectors (HPDs). An HPD combines the use of two technologies – vacuum technology and solid-state technology – to produce a highly sensitive, granular device capable of recording Cherenkov photons over the wavelength range $200 \rightarrow 600$ nm. The technologies have been developed in close collaboration with industry[1] [1]. Under constant and rigorous testing the HPDs of the RICH detectors have met (and in many cases exceeded) their original design specifications. An overview of the achievements of the RICH detectors is given in Ref. [2].

An HPD consists of a silicon detector anode assembly encapsulated in a vacuum envelope as illustrated in Fig. 1(a) and (b). The vacuum tube has a 7 mm-thick quartz entrance window coated with an S20 multi-alkali photocathode. Photoelectrons emitted from the photocathode are accelerated (at a potential ≤ 20 kV) and focussed onto the pixelated silicon detector. The cross-focussing electrostatic field is shaped by electrodes at intermediate potentials. The anode is bump-bonded to a readout chip that provides a binary output—a pixel is considered to have been hit if the detected signal exceeds a given threshold. The sensor chip is divided into 256×32 pixels each with size $62.5\,\mu m \times 500\,\mu m$. Groups of 8 pixels are read out in logical OR-mode to give an effective 32×32 channel array with granularity at the window entrance of $2.5\,mm \times 2.5\,mm$. Comprehensive testing of each HPD is performed to ensure its suitability in the RICH detectors, yielding excellent results with a total pass rate $> 98\%$. One in 10 HPDs are also tested for their quantum efficiency—results have shown a significant improvement in quantum efficiency over the course of production as shown in Fig. 2(a) [3]. HPD thresholds are tuned to maximise the signal-over-noise level. Test pulses of variable charge size are injected at the input to the chip to obtain the optimum threshold above which a pixel is counted as "hit". On average, a threshold of $1060e^-$ is obtained that is sufficiently smaller than the average signal charge of a photoelectron ($5000e^-$) and sufficiently larger than average noise levels ($140e^-$ as shown in Fig. 2(b) [3]). This has yielded signal-to-noise ratios exceeding 25. These tests cover only a fraction of the full test procedure for an HPD.

2. Experimental testing in the RICH detectors

Pairs of HPDs are connected to Level-0 front-end electronics boards, mounted on-detector. The HPDs and Level-0 boards are then mounted onto columns which also include low- and high-voltage boards to power the HPDs [1]. The columns are staggered to maximise the total sensitive area. Two RICH detectors are used for particle identification at LHCb: RICH1, located upstream of the magnet, is used for identification of low-momentum charged particles and uses Aerogel and C_4F_{10} gas as radiators; RICH2, located downstream of the magnet, is used for identification of high-momentum charged particles and uses CF_4 gas as a radiator. Pairs of photo-detector arrays are used in both RICH detectors, located above and below the beam pipe for RICH1 and to either side of the beam pipe for RICH2. Each RICH2 array consists of 9 columns of 16 HPDs, and each RICH1 array consists of 7 columns of 14 HPDs. The combined detector planes are shown in Fig. 3. In total the two RICH detectors employ 484 HPDs.

The HPDs of the RICH system are subjected to continuous testing to ensure optimal operation. When the HPDs are tested in dark conditions (with no external light incident on the photodetector arrays) the measured hit multiplicities are used to identify a number of features such as noisy pixels, disabled readout boards, stray light, or temperature changes. Fig. 3(a) shows a distribution of pixel hits on

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[1] Photonis-DEP, BV, NL-9300 AB Roden, Netherlands as main industrial partner.

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doi:10.1016/j.nima.2010.11.003

the two panels of RICH1 under dark conditions. Each HPD receives on average <0.1 photoelectrons per event in dark conditions.

The HPDs are also brought under illumination from a continuous-wave laser source, testing the response to light. Fig. 3(b) shows the effect of a laser light source on the distribution of pixel hits on RICH2. The circular projection of the photocathode image on the chip can be clearly seen for each HPD. Under laser illumination typically >3 photoelectrons are recorded per event per HPD.

Ion feedback refers to the process where a photoelectron ionises a residual gas molecule in the body of the HPD. This positive ion is accelerated towards the photocathode, where it causes the emission of a shower of secondary electrons. These in turn generate on the silicon chip a large cluster of pixel hits, which appear with a delay of typically 250 ns after the original photoelectron. The ion feedback is therefore an indication of the degree of vacuum degradation in the HPD body. The elevated photoelectron rates experienced under laser light allow an accurate measurement of the ion feedback rate for all HPDs. It has been found that the majority of HPDs retain an excellent vacuum quality, with 75% of low ion feedback rate ($<1\%$ ratio of large clusters to total clusters) as shown in Fig. 4(a). High ion feedback ($>5\%$) is strongly linked to self-sustaining ionisation of HPDs where the following requirement is met:

$$p_{Ionisation} \times N_{Electron} > 1 \quad (1)$$

$p_{Ionisation}$ is the probability of gas ionisation (proportional to the degree of vacuum degradation) and $N_{Electron}$ is the emitted electron multiplicity. 35 out of 51 HPDs with ion feedback exceeding 5% have displayed self-sustaining ionisation. 73 HPDs have so far been removed from the RICH detectors after passing the threshold of 5% ion feedback and displaying self-sustaining ionisation. The removed HPDs have been returned to Photonis (see footnote 1) for retesting, and have or are now being used as replacements. Generally, the ion feedback of an HPD has been found to increase linearly over time. By fitting the increase linearly (and using a suitable ion feedback threshold of 5%) we can extrapolate forward in time and predict when an HPD is expected to cross this threshold and become a candidate for self-sustaining ionisation. We expect

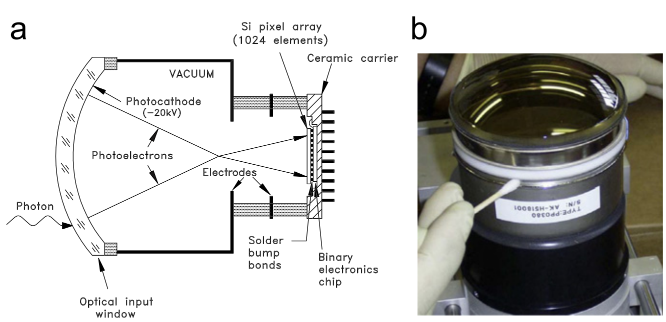

Fig. 1. (a) Schematic of an HPD. (b) Photograph of an HPD.

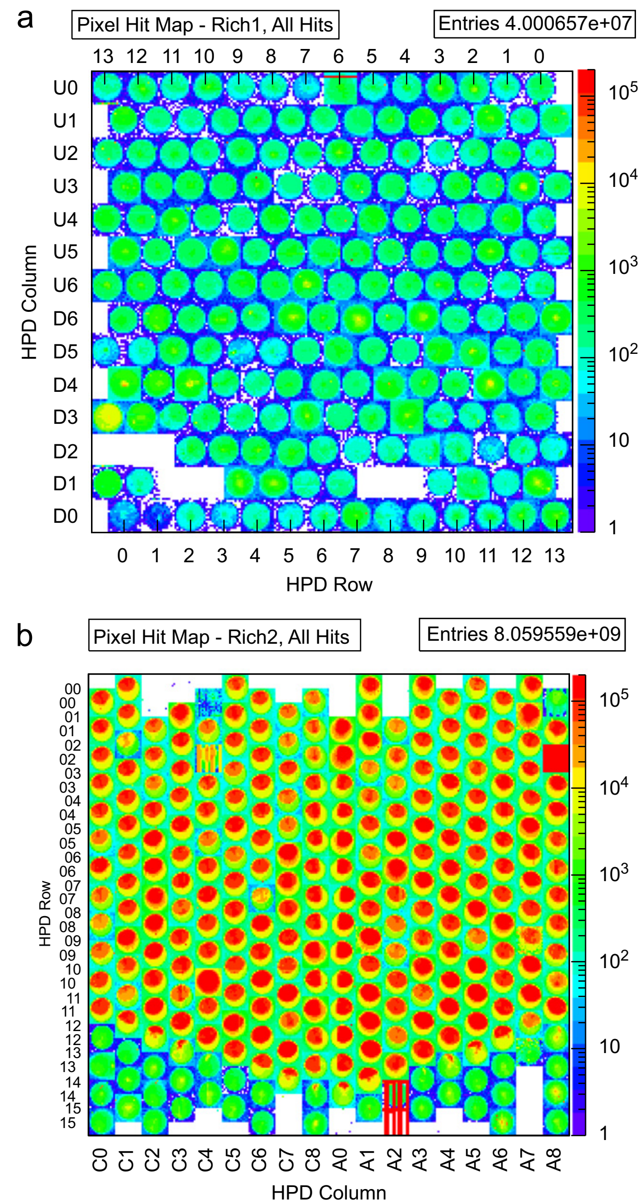

Fig. 3. (a) RICH1 pixel hitmap under dark conditions. Missing HPDs are due to errors in Level-0 board configuration. (b) RICH2 pixel hitmap under illumination from laser light. HPDs at the bottom of the RICH detector receive smaller light intensities due to a shadowing effect from the laser. Missing HPDs have been removed due to vacuum degradation problems.

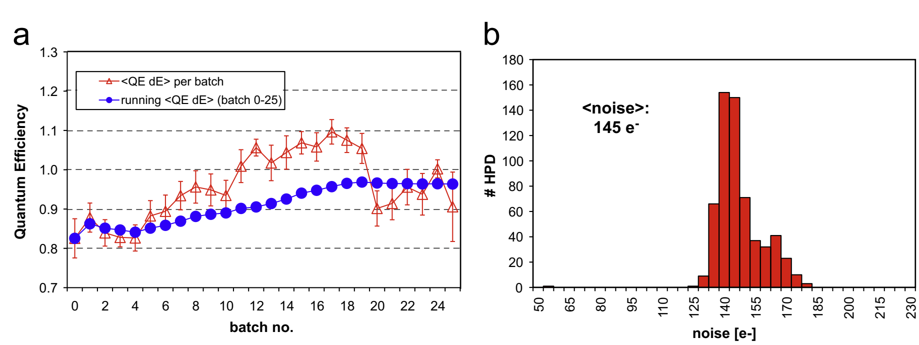

Fig. 2. (a) Batch-by-batch development of quantum efficiency. (b) Distribution of noise levels (e^-) for all tested HPDs.