Analysis of the RICH beam-tests
in September 2006

Internal Note

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Abstract

The LHCb experiment at the LHC (CERN) has been optimised for high precision measurements of the beauty quark sector. Central to the LHCb particle identification strategy are two Ring Imaging Cherenkov (RICH) detectors. The RICH system uses custom-built pixel Hybrid Photon Detectors (HPDs) to measure the Cherenkov photons over the wavelength range 200-600nm. A set of three times 16 HPDs from the production used for the LHCb experiment has been tested in a beam test using the SPS facility at CERN. The data has been recorded with a complete setup of the detector electronics, data-acquisition- and monitoring system used for the final setup of the LHCb experiment. The analysis of the data recorded during the beam test has been done using the full LHCb simulation and reconstruction software framework.

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1 Introduction

The LHCb experiment at the LHC (CERN) has been optimised for high precision measurements of the beauty quark sector. Its main objective is to precisely determine and over-constrain the parameters of the CKM mixing matrix, and to search for further sources of CP violation and new physics beyond the Standard Model in rare B-decays.

Efficient particle identification at high purities over a wide momentum range from around 1 to 100 GeV/c is vital to many LHCb analyses. Central to the LHCb particle identification strategy are two Ring Imaging CHerenkov (RICH) detectors which use Silica Aerogel and $C_4F_{10}$ and $CF_4$ gas radiators. The RICH system uses custom-built pixel Hybrid Photon Detectors (HPDs) [1] to measure the
Cherenkov photons over the wavelength range 200-600nm. Figure 1 shows a schematic overview of the HPD configuration. Each HPD detects photons in using a silicon pixel anode with 1024 channels. The sensor is divided into $256 \times 32$ pixels of an area $62.5 \times 500 \mu m^2$ where each pixel is bump-bonded to one channel of the binary read-out chip. Eight pixels are grouped together by a logical OR leading to effectively 1024 pixels of $500 \times 500 \mu m^2$.

The vacuum tube has a 7 mm thick quartz entrance window which is coated with an S20 multi-alkali photo-cathode on the inside. The typical quantum efficiency with which an incident photon is converted into a primary photo-electron is $\approx 25\%$ at 270 nm. Photo-electrons emitted from the cathode are then accelerated onto the anode assembly by a 20 kV cross-focusing electron optics. Each HPD is surrounded by individual magnetic shields with the final dielectric insulation, whereas previous beam-tests were performed using unshielded HPDs.

A total of 484 HPDs cover an active area of $2.6 m^2$, leading to a granularity of $2.5 \times 2.5 mm^2$. The time-resolution of the photo-detectors is compatible with the LHC bunch-crossing rate of 25 ns. In addition, the on-detector electronics must be radiation tolerant to a dose of $\approx 3 kRad$ per year.

Photon detectors satisfying these constraints have been developed in close collaboration with industry. Previous beam-tests [2] have successfully tested the design of individual components and demonstrated that they are able to fulfill and even succeed the stringent requirements posed by the challenging LHCb physics programme.

To test the overall performance of the final components and exercise the complete RICH operation and data-acquisition a beam-test has been performed in September 2006 using the SPS facility at CERN. The structure of the particle beam provided by the accelerator has been configured to match the later operating conditions of the LHC. 48 HPDs from the final production have been installed in the test-setup together with the final versions of the read-out electronics and data-acquisition system used for the later physics data-taking with the LHCb experiment. The data-quality has been monitored online with an early version of the LHCb RICH online-monitoring software. Data recorded at this beam-test is analysed using the full LHCb reconstruction and analysis software framework and simulation studies are performed using the official LHCb simulation and digitisation software. The tests therefore provide a unique opportunity to test the RICH operations, data-acquisition and subsequent analysis in an environment as close to the one anticipated for the LHCb experiment as possible. The beam-test is therefore an important milestone in the overall preparations and test of the RICH detectors readiness prior to the installation in the LHCb experiment.

2 Beam-test Setup

2.1 Experimental Setup

The beam tests were performed in the North Area of the Prevesin site at CERN. Figure 2 illustrates the experimental setup of the RICH detector used during the beam-tests. The detector consists of a
A radiator vessel filled with either \( \text{N}_2 \) or \( \text{C}_4\text{F}_{10} \) gas as Cherenkov radiator medium. A beam consisting of mainly pions \( (p \approx 80 \text{ GeV/c}) \) with small admixtures of kaons, protons and electrons was obtained from the SPS facility at CERN and directed through the light-tight radiator vessel. Beam particles entered through a thin aluminium foil. Cherenkov photons generated by the particles traversing the radiator are then reflected to the detector housing using an adjustable parabolic mirror. The mirror has a focal length \( f = 1016 \text{ mm} \), a diameter of 200 mm and a reflectivity of more than 90% over the wavelength range of 225 - 450 nm. The detector housing is separated from the radiator vessel by a transparent quartz window and contains three fully assembled RICH columns. Each column consists of 16 HPDs with the corresponding high-voltage supply and low-level read-out electronics [3]. The HPDs on the three columns are arranged in a close-packed setup which is also used in the LHCb experiment. The detector plane is fixed at a distance of 1047 mm from the mirror centre located such that the Cherenkov rings produced by the \( \text{N}_2 \) radiator are fully contained within a single HPD. In addition, the test-setup is equipped with light-emitting diodes which illuminate the photo-detectors to allow measurements of various HPD properties. The intensity of the LED light source was chosen such that the least illuminated HPDs were hit by 1 - 2 photons per event.

Two bare silicon pixel anodes from the HPD production were placed on either side of the RICH test-setup along the beam direction and equipped with read-out electronics. Using this setup the position of the beam particle traversing the detector configuration can be obtained at two points which allows to represent the particle trajectory by a straight line between the silicon pixel sensors. The upstream tracking station was positioned a short distance in front of the entrance window to the Cherenkov radiator medium volume, and the downstream station was placed behind the parabolic mirror at the other end of the radiator volume. The two pixel chips were both positioned with their sensitive side facing the radiator volume, so as to reduce the effect of the multiple scattering of the beam through the pixel chips on the track resolution. The chips were also tilted backwards away from the radiator volume so that the beam would not pass through the level 0 electronics behind them. The pixel chips were connected to the same level 0 data acquisition electronics as used for the HPDs used to detect the Cherenkov light. Consequently the tracking devices could be triggered and read out with the same system as the HPDs.

The test setup was completed by the installation of two plastic scintillators placed in the flight path of the beam particles. A coincident signal from both scintillators was used to start the data-acquisition.
2.2 Trigger and Data-Acquisition

⇒ Steve

3 Simulation of the Beam-test

3.1 Overview

A simulation of the Beam-test setup has been created in order to understand the role played by various effects in the different analyses performed on the data obtained. The simulation was implemented in Gauss, the LHCb simulation package, using the Geant4 framework to model particle interactions with matter. Once converted into the correct format, the simulated data can be analysed in exactly the same way as real data, and by changing various parameters in the simulation it is possible to see how they affect the reconstructed Cherenkov angle, photoelectron yields, etc.

3.2 Simulation

The Beam-test simulation detector description is based on the RICH2 detector description used in the LHCb DC06 Monte Carlo production. The gas radiator volume was altered to match the geometry of the SSB, and a single mirror segment used. The full RICH2 HPD planes were included, meaning there is a total of 18 HPD columns in the simulation (as opposed to 3 in the Beam-test setup) but the extraneous columns can be ignored. For ease of reconstruction, the trackers were implemented as complete HPDs rather than bare anodes, and the unwanted processes generated as a result (primarily Cherenkov generation and inelastic scattering in the HPD quartz window) were killed by altering the Geant4 physics code.

Particle generation is done via a ParticleGun that (by default) creates single, stable particles with user-defined type and momentum. Options have been added to the ParticleGun to produce a beam of particles with the same composition as the real beam provided by the SPS (80% Pions, 10% electrons, 8% Kaons and 2% Protons; the charge of these particles does not concern us as there is no magnetic field), and to allow multiple particles per events.

Figure 3 View of the simulated Beam-test setup from visualisation package Panoramix, showing tracking stations, HPD plane and mirror segment, with a pion passing through the setup generating Cherenkov photons. Note the extraneous HPD columns which are ignored when the data is analysed.
4.1 Hit selection and clustering

The first step in the selection of events on the basis of tracking data was that an event would be rejected if there were no hits recorded on either tracker. An event would also be rejected if there were more than some fixed number, configurable by the user, of hits on either tracker.

The clustering algorithm was designed for the purpose of identifying small clusters, that could reasonably be said to be caused by a single incident charged particle, incident close to a boundary between pixels, or with other effects causing a genuine signal in one pixel to result in a signal in neighbouring pixels also.

Hits in pixels that were horizontally, vertically or diagonally adjacent were to be considered as potentially being caused by the same incident charged particle and therefore could be considered as a cluster. The algorithm should be capable of treating a row of 3 pixels as being one cluster (if this was set in the options at the time of analysis) but not two pixels separated by a pixel with no hit. No attempt is made to recognize cases where pixels are inefficient at registering hits, and inefficient pixels may cause clusters to be missed by the algorithm.

The algorithm defined a “cluster” of hits as a group of at least one hit all positioned within a radius of 1.1 pixels of a central point (whose co-ordinates are the average of the co-ordinates of all the hits in the group), with the restriction that there must be a hit within a distance of 0.6 pixels of the central point.

The algorithm operated by looking at all the hits in a given event on a tracker, then calculating the “centre of gravity” of the hits, treating this as the centre of the putative cluster, and then assessing how close all the hits were to the cluster centre. If all hits were within 1.1 pixels’ distance (i.e. within 500 µm) of the cluster centre, and the pixel closest to the putative cluster centre had a hit, then this would be classed as a cluster. Otherwise, the hit furthest from the cluster centre would be removed. The process would then be repeated until the hits formed a cluster that satisfied the definition given above. When a cluster had been found, the hits that had been removed and had not so far been clustered were looked at again, to repeat the process of looking for clusters with these hits.

The pixel closest to the putative cluster centre was required to have a hit, so as to try to avoid grouping 2 nearby clusters into one cluster, e.g. so that a row of 3 pixels could be classed as a cluster, but not a group of two hit pixels, separated by one pixel with no hit.

With the data recorded at the beam test, and the low number of events that featured multiple hits on a single tracker in a single event, and even lower number of events that featured multiple hits close enough to each other to be considered as clusters, a detailed statistical analysis or check of the configuration of the clustering algorithm with the numbers 0.6 and 1.1 is not possible.

The numbers 1.1 and 0.6 are chosen on the basis of considering the values needed to exclude or include particular arrangements of hits as clusters. The number of possible cluster configurations with our definition is limited enough, and the cluster sizes for which the algorithm is intended are small enough that this can be done. The number of different values that can be taken by the distance between a hit and its cluster centre is also small, for the same reason. Consideration of the possible cluster configurations results in a number of constraints on the parameters. The first number, chosen as 1.1, must be:

- larger than 0.5 if we are to select a set of 2 hits that are neighbours along a vertical or horizontal line as a cluster
- larger than \(\sqrt{2}/2\) if we are to select a set of 2 hits that are neighbours on a diagonal line as a cluster
- larger than 1 if we are to select a set of 3 hits in a straight line

The second number, chosen as 0.6, must be at least 0.5 for a set of 2 hits that are neighbouring on a horizontal or vertical line to count as a cluster. A value \(\geq 1\) would result in two hits in a horizontal line separated by one non-hit pixel to count as a cluster. The number must then be chosen to be less than or greater than \(\sqrt{2}/2\) in order to exclude or include, respectively, a configuration of 2 hits neighbouring on a diagonal line.
4.2 Track construction and selection

At this point, a user-configurable cut could be applied, to reject an event if there were more clusters remaining than desired. If the event was not rejected at that stage, then all possible tracks, each joining a different pair of upstream tracking cluster and downstream tracking cluster, were considered. For each possible track, the differences between the $x$ and $y$ co-ordinates of the clusters in each tracking pixel plane were calculated and compared with the Gaussian fitted to the distributions from the whole run. If $\Delta x$, the difference between the two $x$ co-ordinates (after an adjustment was made for the fact that the two pixel chips were facing each other and that their $x$ axes were therefore orientated in opposite directions), was more than $3\sigma$ away from the centre of the Gaussian fitted to the $\Delta x$ distribution of the whole run, then the possible track was rejected. If the number of remaining possible tracks after this process was still greater than 0 and less than a user-configurable maximum number, then the event was accepted and track objects were created, to be used by the latter stages of reconstruction in analysis of the Cherenkov angle.

In addition to the track selection in the tracking algorithm code specific to the beam test, the general RICH reconstruction code selects the track from which it thinks each photon is most likely to originate. This is only necessary if the test beam tracking algorithm is configured such that it is possible for it to provide more than one track for the later stages of reconstruction that then use the tracks reconstructed by it.

4.3 Tracking performance

Subsection yet to be written

- Lack of inefficient pixels
- Lack of noisy pixels (for the most part)
- Relatively uniform distribution of hits across pixel chips within some sort of trigger scintillator silhouette/beam profile
- Fraction of events that have no tracker data on at least one tracker
- Fraction of events that have exactly one hit on both trackers
- Fraction (small) of events that actually involve multiple hits
  - How many involve clusters
  - How many of these are non-trivial, i.e. more than 2 hits/tracker/event
- How many involve multiple hits that are separated by relatively large distances
- Performance of the actual tracking, rather than just the clustering

etc. in both data and MC and comparison between them.

5 Alignment

5.1 Overview

5.2 Alignment of the Tracking Stations

In order to fully exploit the tracking information provided by the pair of bare silicon pixel anodes, it was first necessary to align their orientation in software space. As a starting point, these two pixel chips were positioned within the detector database description according to surveyed measurements taken at the end of the testbeam run. Within the reconstruction software, tracks were formed from events with only one hit on each pixel and the direction of these tracks were determined within a spherical-polar coordinate system, defined as having its $z$-axis coincident with the beampipe axis. For tracks travelling perfectly down the beam axis, one would expect the polar angle, $\theta$, distribution to have a mean centered at 0 radians, respectively. However, as shown in Fig. 4(a), the distribution formed with the original alignment had a mean displaced by $\sim 5$ mrad from that expected. It was, therefore, necessary to correct for this misalignment.

To align the tracking pixel chips such that the reconstructed tracks had a mean $\theta$ distribution of zero, the distributions of the $x$ and $y$ coordinates (i.e. planes perpendicular to the beam axis) for each hit
on both pixel chips, accumulated during a typical run, were considered. The \( x \) and \( y \) positions of the tracking chips were then adjusted accordingly until the means of these distributions coincided with the defined coordinates of the beam axis in these respective planes. Correcting the misalignment in this manner resulted in the \( \theta \) distribution shown in Fig. 4(b). Additional confirmation that reliable alignment had been achieved comes from considering the azimuthal angle, \( \phi \), distribution of all tracks, shown in Fig. 5. Since there is no constraint on this angle, one would expect a uniform distribution between \(-\pi/2\) and \(+\pi/2\) rads. This is, indeed, what is seen in Fig. 5.

5.3 Alignment of the Mirror and HPDs

5.3.1 Misalignment Effects

The testbeam analysis was performed using the full LHCb reconstruction software. In order to correctly reconstruct the events and extract accurate measurements it is necessary for the detector hardware to be correctly modeled in the software package. Discrepancies between the actual hardware setup used and the software description cause misalignment effects that must be identified and compensated for. Of particular importance was the modeling of the mirror used in the testbeam setup as this was rotated between runs in order to focus the Cherenkov light onto different areas of the photodetector plane. Other possible discrepancies between the hardware setup and the software de-
scription considered include the positioning of individual HPDs and the variation between HPDs of the position of the internal silicon sensor.

When the data is reconstructed the software uses information from the tracking to determine the path of particles through the radiator volume. The hardware description and mirror position is used to project the path of the particle onto the photodetector plane in order to associate the particle with a cherenkov ring. For a correctly aligned system the particle projection will lie in the centre of the ring and will be used to calculate the Cherenkov angle $\Theta_c$. A misalignment in the mirror position, for example, would cause the projected track to be displaced from the ring centre. This would reduce the resolution of the reconstructed Cherenkov angle.

\[ \Delta \Theta_c = a \cos(\phi) + b \cos(\phi) \] (1)

This method was used to accurately determine the correct mirror positions to reconstruct the $N_2$ data runs taken. Over the 16 runs four different mirror positions were used. The data was reconstructed using an estimated position (see figure 6), the fitting method was used to determine the precise mirror position, and the reconstruction re-run to extract the final measurements (see figure 7).

\[ \text{NOTE: We may want to redo these plots after the offset in } \Delta \Theta_c \text{ has been removed} \]

5.3.3 Alignment of HPDs

For the $N_2$ runs, as in each run the Cherenkov ring is contained entirely on a single HPD, misalignment contributions from the relative positioning of HPDs (or the Silicon sensors inside the HPDs) can be ignored. This is not the case for $C_4F_{10}$ data as the larger Cherenkov rings are spread across three or four different HPDs. Alignment effects can be split into ‘global’ misalignments that effect the whole ring, and ‘local’ misalignments that indicate a specific HPD is misaligned with respect to
Misalignment effects from the possible rotation of the Silicon sensor were investigated using simulated data. Variations in the relative demagnification laws between HPDs were investigated by comparing relative sizes of $N_2$ rings. Both were considered to have a minimal impact on the alignment situation.

====NOTE: I am not 100% sure of this yet - I have some results to show at the next meeting====
6 Charge Sharing

6.1 Overview

The photoelectron signal on an HPD is optimally contained in a single pixel, but will create a signal over threshold in 2 or more adjacent pixels with a probability of around 3 known as a charge share. It is important to know the charge sharing probability for each HPD in order to control the measurements of photoelectron yield to the percent level. The test-beam setup contained a set of red LEDs which could uniformly illuminate the central HPDs. These LEDs were installed as a means to measure the probability that a photo-electron emitted from the photo-cathode of the HPD would result in a charge share. The LED absolute intensity was not a priori known, except that its fluctuation in intensity was orders of magnitude less than would affect our analysis. The LEDs provided illumination onto the HPDs while beam was off so that it could be assumed that no particles were passing through the HPD box and causing background Cherenkov photon light.

6.2 Ion Feedbacks and Micro Discharges

Ion feedbacks and micro discharges account for around 5 percent of hits in the HPDs. They tend to be clustered in large groups of adjacent pixels of average size of a few LHCb pixels. Tails of the distributions extend down to small cluster sizes of 1 or 2. Unchecked, they would be a more serious background to charge sharing (3% of hits) than they are to ordinary data.

An ion feedback signal occurs when a residual ion from the low pressure gas inside the tube collides with the photo-cathode. The shower of electrons strike the pixelated anode, usually distributing charge across many pixels. The HPDs were produced in a high but imperfect vacuum. As such, residual gas atoms from the atmosphere inside the production facility remain in the HPD. Over time, helium can leak into even a sealed HPD. To reduce this, the HPDs are stored in gas extremely low in helium. This adds to our ion feedback background. Ionisation probability is proportional to the photo-electron flux and the gas density in the tube. Electrons can strike one or both electrons from a helium atom. The helium ion then drifts in the electric field of the HPD toward the photo-cathode. The field configuration is such that the ions tend to strike the photo-cathode in the central region. This high energy ion ejects tens of electrons from the cathode which are accelerated toward the anode centre.

A micro discharge is a spark from near the photo-cathode due to electrical breakdown of the gas around the tube. This occurs at a high rate while the tubes settle in a high voltage environment. The tubes stabilise after a few hours so that the micro discharge rate reduces by orders of magnitude. The sparks
emit large numbers of photons concentrated in a small area around the edge of the photo-cathode. A microdischarge tends to create a collection of clustered hits near the edge of the photo-cathode image on the pixel chip anode. The tails of this distribution again can mimic charge sharing.

The HPDs were ramped to 20KV and left for a few hours before the analysis was undertaken in order to keep the micro discharge rate to a minimum.

6.3 Data

Around $10^6$ events were taken, with the LED intensity constant and set so that an average four photoelectrons per event were seen for the central HPDs. The integrated flux of photoelectrons for HPD 222 is shown in figure 10. One can see that there is some increase in average intensity toward the HPD centre. I will show evidence for some of this at least to be ion feedbacks.

We start this section with the definition of charge sharing. Charge sharing is defined as:

$$P(CS) = \frac{N_{phot_{adj, single}}}{N_{phot_{all}}}$$  

where:

- $P(CS)$ = Probability of charge share
- $N_{phot_{adj, single}}$ = Number of adjacent pixels with signal due to the same photo-electron
- $N_{phot_{all}}$ = number of photoelectrons in total.

The subtleties of the definition will become apparent to the reader

We begin analysis of data by combining adjacent hit pixels into clusters of hits, both on the diagonal and on the straight 11. We can then observe those hits which are isolated and those which form clusters of 2 or more hits. By the most naive assumption, the double clusters are assumed to be charge shares and the singles to be ordinary photo-electron hits. This simple cluster counting puts this first charge sharing estimate at the overestimate of 10% for a HPD.
6.3.1 Ion feedback and discharges Cuts

The charge sharing estimate is sensitive to the ion feedbacks and discharges. I fit the 1D distribution of hits on an example HPD (here 222). We can see in figure 12 that the 1D distribution of hits is can be described with a Poissonian (with $\chi^2/DOF = 19$) up to 5 hits, albeit poorly. Beyond 5 hits the fit quality rapidly worsens. I expect that effects compatible with a single Poisson are dominant across the HPD in the range 0-5 hits and other effects begin to matter outside of this range. I assume that the single Poisson is due to the LED photon hits and the tail at high hit rate is from the ion feedbacks or discharges. It is then sensible to select those HPDs with 5 or less hits in an event as ion feedback and discharge free. In practice I place the cut not on the number of hits, but on the number of clusters so as not to bias the charge sharing estimate.

Ion feedbacks and discharges tend to be concentrated in clusters. The probability of 3 legitimate photoelectrons striking adjacent pixels in an event with 5 hits is negligible. Any cluster of 3 pixels or more is assumed to be background and that HPD is excluded from further analysis in the event.

With these cuts applied, the $\chi^2/DOF$ for HPD222 improves to 1213. It is known that ion feedbacks are concentrated toward the HPD centres and discharges toward the edge. The HPD can then be split into regions (I choose 2 regions, inner and outer), with the dominant background then being either ion feedbacks or discharges. The degree to which ion feedbacks and discharges still dominate can be deduced by comparing the charge sharing estimates for the inner and outer regions. If these are consistent with each other the background may be considered negligible. Failing this, if a HPD is known to have a high proportion of one particular background, the region of background can be excluded and the charge sharing taken from analysis only in the low background region.

The fit to the distribution of hits is improved by using a different functional form. We describe the distribution with a Poisson for the signal plus a Gaussian to describe the background from ion feedbacks and discharges remaining after cuts. By way of example, from figure 14, one can see that the wide underlying Gaussian has a larger relative normalisation constant in the inner region of HPD222 than the outer, indicating that the dominant background is consistent with ion feedbacks in the central region. The dominant background type and region varies from HPD to HPD. The hits from the region with lowest fitted background fraction is in all cases used to estimate charge sharing.

6.4 estimating the number of double clusters from 2 independent photoelectrons

Two adjacent pixels can be struck by two independent photoelectrons. These “legitimate doubles” will increase the charge sharing estimate and some attempt to correct for them must be made. I simulate
**Figure 13** integrated hits after cuts across the HPD 222 for 450000 events, with Poisson fit from 0-5 hits

**Figure 14** integrated hits across the HPD 222 for 450000 events, with Gaussian + Poisson as the fit function across the range for (a) inner region, (b) outer region
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Figure 15 Convergence of the charge sharing estimate including the simulation of legitimate doubles

Figure 15 shows the convergence of the charge sharing estimate. The hits on the HPD assuming a uniform illumination across the HPD active area. The hits from an HPD that survives the above cuts are assumed to be purely from single photoelectrons or charge shares. Charge sharing is assumed only to cause signals on pixels adjacent to each other or on the diagonal. We desire to simulate only the single photoelectrons and ignore the charge shares.

The number of hits on the HPD is taken from a real event. We then distribute this number of hits uniformly across the active area of a simulated HPD. The active area is taken to be a circle of radius 13.5 pixels centred on pixel co-ordinate (15.5, 15.5). All pixels are assumed to be perfect squares.

The first estimate of the legitimate double probability is then the number of adjacent hits seen in the simulation. The charge sharing probability is then \( P(\text{any double}) - P(\text{double in simulation}) / \sum(n\text{hits}) \). This simple treatment does not attempt to take into account that some of the hits on an HPD are from charge shares, and thus the number of hits \( \neq \) to the number of photoelectrons. The simulation is then extended to allow for some charge-sharing. Each time a double cluster of hits is encountered in the data from an HPD, a probability that this is a charge share is assigned. This probability is taken as the charge share probability / legitimate doubles probability, and is taken as 50% to first approximation. A uniform random number is generated and if the random number is less than the charge sharing/legitimate doubles ratio, a single hit is then simulated, else two hits are simulated. At the end of the simulation, the charge sharing estimate is recalculated. This changes the simulation into an iterative procedure. It is shown in figure 15 that the iteration converges to a value of charge sharing rapidly, to within a 0.1% error within 4 iterations of the code.

6.5 Conclusion

Out of the 48 HPDs, 7 had No data. 32 HPDs had final charge sharing estimates for which the analysis of the inner and outer regions agreed to within 0.2% and the remaining 9 either had statistical errors above 0.2% or had discrepancies of up to 2% between the inner and outer regions. There were two cases of discrepancy of interest, as they apply to HPDs within the chernekov ring region of the light tight box. For these two cases it was observed that only one of the backgrounds dominated, thus the charge sharing estimate from the HPD region relatively free of the dominant background is used. The results of the charge-sharing analysis are summarised in table 16.

7 Photo-electron Yields

7.1 Overview

The efficiency of the RICH detectors can be evaluated by counting the number of photons per ring for Chernkov rings in the gas radiators. The ultimate aim of the photon yield studies is the determination
Analysis of the RICH beam-tests in September 2006

Internal Note

Issue: 1

Photo-electron Yields

<table>
<thead>
<tr>
<th>HPD ID</th>
<th>charge-sharing fraction</th>
<th>HPD ID</th>
<th>charge-sharing fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>3%</td>
<td>223</td>
<td>2.4%</td>
</tr>
<tr>
<td>101</td>
<td>2%</td>
<td>250</td>
<td>No Data</td>
</tr>
<tr>
<td>108</td>
<td>3%</td>
<td>251</td>
<td>No Data</td>
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<tr>
<td>109</td>
<td>4%</td>
<td>256</td>
<td>3%</td>
</tr>
<tr>
<td>116</td>
<td>1.6%</td>
<td>257</td>
<td>3%</td>
</tr>
<tr>
<td>117</td>
<td>1.6%</td>
<td>264</td>
<td>No Data</td>
</tr>
<tr>
<td>146</td>
<td>3.3%</td>
<td>265</td>
<td>2.4%</td>
</tr>
<tr>
<td>147</td>
<td>2%</td>
<td>266</td>
<td>2.3%</td>
</tr>
<tr>
<td>14</td>
<td>2.7%</td>
<td>267</td>
<td>2.5%</td>
</tr>
<tr>
<td>150</td>
<td>5%</td>
<td>282</td>
<td>3.0%</td>
</tr>
<tr>
<td>151</td>
<td>2%</td>
<td>283</td>
<td>2.5%</td>
</tr>
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<td>156</td>
<td>2.5%</td>
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</tr>
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<td>157</td>
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<td>15</td>
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<td>60</td>
<td>No Data</td>
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<td>162</td>
<td>2%</td>
<td>61</td>
<td>No Data</td>
</tr>
<tr>
<td>163</td>
<td>2.9%</td>
<td>76</td>
<td>3.2%</td>
</tr>
<tr>
<td>166</td>
<td>8%</td>
<td>77</td>
<td>3.4%</td>
</tr>
<tr>
<td>167</td>
<td>No Data</td>
<td>78</td>
<td>2.9%</td>
</tr>
<tr>
<td>178</td>
<td>7%</td>
<td>79</td>
<td>2.8%</td>
</tr>
<tr>
<td>179</td>
<td>No Data</td>
<td>86</td>
<td>3.0%</td>
</tr>
<tr>
<td>18</td>
<td>3.1%</td>
<td>87</td>
<td>3%</td>
</tr>
<tr>
<td>19</td>
<td>2.6%</td>
<td>88</td>
<td>2.7%</td>
</tr>
<tr>
<td>222</td>
<td>4%</td>
<td>89</td>
<td>4.2%</td>
</tr>
</tbody>
</table>

**Figure 16** Results of the charge-sharing analysis

of a model for photoelectron production and detection that can be checked on the beam test data and used to calculate the expected number of detected photoelectrons per charged particle in the final experiment.

The test-setup was filled with two different Cherenkov radiators during the beam tests, \( \text{N}_2 \) and \( \text{C}_4\text{F}_{10} \). In case of \( \text{N}_2 \) the Cherenkov ring is contained on a single HPD and data is available on three different HPDs. The use of \( \text{C}_4\text{F}_{10} \) has a twofold advantage: the same gas is used in RICH 1, so that results from the beam test are easily translated to the final detector, and its refractive index (and therefore the Cherenkov angle) is high enough that the ring in the photon detection plane covers up to 4 HPDs, allowing timing and performance studies on all columns at the same time.

### 7.2 Event Selection

First, an unambiguous definition of the ring region is needed in order to proceed with photon counting. Hits are then considered to originate from a Cherenkov photon if they lie within the defined ring region. The number of hits in this road per event is then taken as the figure of merit for Cherenkov photon yield and detection efficiency. In order to disentangle as much as possible from ion feedback and background hits induced by radiation timed with the beam or similar unpredictable effects events are rejected if more than three hits are recorded outside the ring region. Also, at least four hits are required inside the road.

### 7.3 Determination of the Photoelectron Yield

The photo-electron yield is extracted by performing a constrained fit to the distribution \( N(n) \) of hit pixels per event in the events that pass the event selection. This fit must take into account:

- Pixel to pixel charge-sharing, \( s \), where one photo-electron produces hits in two neighbouring pixels.
Double hits, \( d \), where hits are lost due to two photo-electrons striking a single silicon pixel and only one hit being read-out due to the binary readout of the pixel chip.

The trigger, a pair of coincidence scintillators, which provides no veto of particle multiplicity.

The beam, which contains a mixture of particles, with approximately 80\% \( \pi^- \), 10\% electrons, 7\% kaons and 3\% anti-protons above the Cherenkov threshold.

The distribution of hit pixels per event, \( N(n) \) is then given by,

\[
N(n) = \sum_{i=\pi,K,p} N_i P(n|\mu_i, s, d) + N_{2\pi} P(n|2\mu, s, d) \times (N_{3\pi} P(n|3\mu, s, d))
\]

where

\[
P(n|\mu, s, d) = \sum_{i=0}^{n} \sum_{j=0}^{\infty} P(n-i+j|\mu) \times P\left(\frac{P}{(n-i) s}\right) \times P\left(\frac{d}{(n-i+j-(n-i+j-1) d)}\right)
\]

and \( P(a|b) \) is the Poisson probability of getting \( a \) given a mean value, \( b \). Eq. 3 is a sum over the possible particle types, the two particle contribution \( N_{2\pi} \) and a possible three particle contribution \( N_{3\pi} \) in the case of \( C_4F_{10} \). \( N_1, N_2 \) and \( N_3 \) are the fitted numbers of events with one, two or three particles.

The \( P(n|\mu_i, s, d) \) (Eq. 4) are Poisson-like probabilities that are the underlying poisson distribution for the number of hits on a ring that is corrected for combinations where hits are gained due to charge sharing or lost due to the binary readout (double hits). The charge sharing probability has been fixed for each HPD to the corresponding measured value (see section 6). The fit has been performed in the range 5 to 30 hits for all runs. In case of \( C_4F_{10} \) the absolute value of \( \mu \) depends on the fraction of ring overlapping the photocathode of the HPD under study. This fraction has been calculated from the geometric distribution of the hits on the anode, by plotting the occupancy as a function of the polar angle \( \phi \) with respect to the fitted centre of the ring. The ratio \( \mu/\Delta \phi \) is taken as the figure of merit for the photon yield. Figure 20 shows a typical distribution of the number of hits in the road and superimposed to data is the resulting fit function.
7.4 Extracting the Photo-electron Yield for $N_2$

7.4.1 Event Selection

The number of events with two or more particles is reduced by requiring that there is only one cluster of hits (track) in each of the tracking stations. This selects approximately 40% of events.

Rings are then fitted to the $N_2$ events on an event-by-event basis (Fig. 7.4.1) and the average ring centre and radius used to define the valid ring region ($\pm 3$ pixels about this average ring position).

This removes events with no Cherenkov ring or large clusters of hits on the anode (that come from charge settling effects) and selects 87% of the events passing the tracker cut.

7.4.2 Determination of the Photoelectron Yield

The mean ($\mu$), number of one particle ($N_\pi + N_K + N_p$) and the number of two particle events are allowed to vary in the fit and the other parameters are either held fixed or expressed in terms of these (this restriction is relaxed in Sec. 7.4.3). An example distribution of hit pixels per event with its corresponding fit can be seen in Fig. 19. The model accurately reproduces the distribution seen in the data. A summary of the yields for each of the three photo-detectors is given in table 1.

<table>
<thead>
<tr>
<th>HPD</th>
<th>Events</th>
<th>$N_{\pi,K,p}$</th>
<th>$N_{2\pi}$</th>
<th>$\mu$</th>
<th>$\chi^2$/NDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>117</td>
<td>15,290</td>
<td>14,876 $\pm$ 125</td>
<td>356 $\pm$ 43</td>
<td>12.41 $\pm$ 0.04</td>
<td>22.72 / 17</td>
</tr>
<tr>
<td>264</td>
<td>23,253</td>
<td>22,756 $\pm$ 155</td>
<td>459 $\pm$ 60</td>
<td>13.08 $\pm$ 0.02</td>
<td>12.47 / 17</td>
</tr>
<tr>
<td>265</td>
<td>20,085</td>
<td>19,593 $\pm$ 143</td>
<td>436 $\pm$ 50</td>
<td>12.60 $\pm$ 0.03</td>
<td>15.59 / 17</td>
</tr>
</tbody>
</table>

Table 1 The fitted hit pixel distribution for the three tubes. The reasonable $\chi^2$ suggest the model is an accurate representation of the data and should be compared to the 10 times larger $\chi^2$/NDF of a simple single Poisson fit.

7.4.3 Evaluation of Systematic Uncertainties

The expected yield for each of the HPDs, using the quantum efficiencies measured by the manufacturer (DEP) is given in table 2. This is calculated from Eq. 5. Here, $L$ is the length of the radiator, $Q$ the quantum efficiency of the HPD, $R$ the reflectivity of the mirror in the SSB, $T$ the transmission of the quartz window that separates the radiator and HPD volume and $n(E)$ the refractive index of the $N_2$ gas.
Analysis of the RICH beam-tests in September 2006

Internal Note

7 Photo-electron Yields

Ref: LHCb-42-2004

Date: August 31, 2007

Figure 19 The observed number of hit pixels per event (points) and fit (line) taking into account pixel-to-pixel charge sharing, the binary readout of the pixel chip and the possible particle multiplicities in the beam.

Table 2 Measured and expected yields in $N_2$ at $T = 22^\circ$C and $P = 960$ mbar. The measured yield includes a small correction for ‘dead pixels’ on the anode and for time alignment. The ratio should correspond to the 80-85% efficiency of the anode.

<table>
<thead>
<tr>
<th>HPD</th>
<th>Measured Yield</th>
<th>Expected Yield</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>117</td>
<td>$12.32 \pm 0.12$</td>
<td>$15.25 \pm 0.77$</td>
<td>$0.81 \pm 0.04$</td>
</tr>
<tr>
<td>264</td>
<td>$13.14 \pm 0.13$</td>
<td>$17.61 \pm 0.88$</td>
<td>$0.75 \pm 0.04$</td>
</tr>
<tr>
<td>265</td>
<td>$12.56 \pm 0.12$</td>
<td>$16.01 \pm 0.81$</td>
<td>$0.78 \pm 0.04$</td>
</tr>
</tbody>
</table>

The final fit result can be found in Table 2. There has been a small change in the preferred yield but for each tube this amounts to less than $1\sigma$. There is an additional factor of 80-85% that is omitted from the expected yield calculation, this comes from the efficiency of the HPDs anode and mainly results from

\[ N = 370eV^{-1}cm^{-1} \times L \int QRT \left( 1 - \frac{1}{n(E)^2\beta^2} \right) dE \]  

The largest contribution to the error on the expected yield comes from an assumed 5% error on the product of $QRT$. The error in Table 2 also includes a small contribution from pressure and temperature variations during the test beam period.

Systematic uncertainties that appear with the measured yield in Table 2 are calculated by introducing a series of Gaussian penalty terms to the fit so that the function minimised is now given by:

\[ \chi^2_{\text{fit}} + \left( \frac{s - \bar{s}}{\sigma_s} \right)^2 + \left( \frac{d - \bar{d}}{\sigma_d} \right)^2 + \ldots \]

and allow the previously fixed parameters to vary ($s$, $d$ etc.) accordingly:

- Charge sharing is typically $s = 3 \pm 2\%$ (a more complete description is given in Sec. 6).
- The probability to lose a hit as a double hit will depend on the number of hits in the ring. In the fit the probability per hit is assumed to be linear with the event size, $(n - 1) \times d$, where $d = 5 \pm 1 \times 10^{-3}$. This quantity is estimated both from a toy model and a ‘fake-event’ method and these give comparable results. In the fake event method hits are selected at random from multiple different events to build a new event that contains only one hit from any one contributing event. Higher order polynomials have been tried but have limited impact on the fit.
- The fraction of kaons and anti-protons in the fit are taken to be $7 \pm 2$ and $3 \pm 2$ respectively [4].
Rutherford Backscattering (18%) at the silicon anode. The final column in Table 2 should correspond to this value. We might expect the values to be smaller than the predicted 80% for two reasons. Firstly due to a reduction in the length of the strobe from 50 to 25 nanoseconds between the laboratory and production system and secondly the general increase in thresholds of the anode that is required to deal with the more noisy environment.

7.5 Extracting the Photo-electron Yield for $C_4F_{10}$

7.5.1 Event Selection

The allowed ring region is defined in the following way. The fit results are the coordinates of the centre of the circle and its radius of curvature. The average values of these parameters, $x_C$, $y_C$ and $R$, together with their standard deviations are computed for all the events in the run whose fit resulted in a $\chi^2/\text{ndf} < 4$. A road is defined as the ring-like region enclosed by two concentric circles. The coordinates of the common centre of the circles are $x_C$ and $y_C$, and the radii are $R + \sigma_R$ and $R - \sigma_R$. Figure ?? shows, for a typical run, the hit distribution on the anode and, superimposed, the road. Similarly to the $N_2$ case we consider a hit on the pixel chip as a Cherenkov photon if it lies within the road. We reject on average 8% of the events by applying this cut. In runs where the Cherenkov rings were focused on three HPDs, we reject by this requirement about 2% of the events.

7.5.2 Determination of the Photoelectron Yield

Timing studies have been performed by tuning a fine delay register on the L0 board, spanning a full period of 25 ns in 12 steps. Figure 21 shows the result of one such scan. We found out that for all tested HPDs and L0 boards the optimal delay setting is 16.67 ns.

For all the runs taken at the optimal timing setting the photoelectron yield per radian $\mu/\Delta\phi$ has been calculated. To check the reproducibility of the results, we compared the photon yield for the same HPD in different runs. We found out that the stability of the result is within 5%, a possible explanation for the run to run deviations lies in a slight non–uniformity of the photocathode in terms of its quantum efficiency, since in different runs different regions of the HPD are illuminated by Cherenkov photons. A summary of $\mu/\Delta\phi$ results is shown in table 3; for each HPD the mean value is taken from all the runs. The average photoelectrons yield is 9/radian, with 10% spread from HPD to HPD. This is
Figure 21  Timing scan results for 3 HPDs. The number of photoelectrons per radian on the ring is plotted against the setting of the TTC-rx fine delay. The thick dotted line at 16.67 ns marks the optimal timing setting.

<table>
<thead>
<tr>
<th>HPD</th>
<th>$\mu/\Delta\phi$ (photoelectrons/radian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>10.7 ± 0.2</td>
</tr>
<tr>
<td>88</td>
<td>8.3 ± 0.5</td>
</tr>
<tr>
<td>116</td>
<td>8.6 ± 0.3</td>
</tr>
<tr>
<td>117</td>
<td>8.5 ± 0.4</td>
</tr>
<tr>
<td>222</td>
<td>9.0 ± 0.5</td>
</tr>
<tr>
<td>223</td>
<td>8.9 ± 0.3</td>
</tr>
<tr>
<td>265</td>
<td>8.8 ± 0.3</td>
</tr>
<tr>
<td>282</td>
<td>9.4 ± 0.6</td>
</tr>
<tr>
<td>283</td>
<td>9.2 ± 0.6</td>
</tr>
<tr>
<td>mean</td>
<td>9.1 ± 0.7</td>
</tr>
</tbody>
</table>

Table 3  Summary of the photoelectron yield per radian per charged particle in $C_4F_{10}$.

consistent with the different quantum efficiencies of the photon detectors measured during the quality assessment phase. === To be cross checked with Test Station people ===

8  Cherenkov Angle Resolution

8.1  Overview

8.2  Demagnification of Photoelectrons

⇒ Antonis, Andrew,

8.3  Cherenkov Angle Resolution for $N_2$

⇒ Andrew

8.4  Cherenkov Angle Resolution for $C_4F_{10}$

⇒ Hugh
9 Conclusion

⇒ all

10 References


