

Use of lenses to increase the RICH photodetector coverage

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Abstract

A novel lens arrangement is described, that can be placed in front of multianode photomultipliers to increase their geometrical coverage to almost 100%. The performance of the system is insensitive to the photon incident angle out to 400 mrad, allowing its use with aerogel as well as gas radiators. The array of lenses can also serve to separate the photodetectors from the radiator gas, and as only a single gas/lens interface is introduced there is no penalty from reflection loss.

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1 Introduction

The RICH detectors of LHCb require the use of photodetectors sensitive to single photons, covering a large area (2.9 m^2 in total) with fine granularity ($2.5\text{ mm} \times 2.5\text{ mm}$) and the highest possible efficiency. The efficiency is the product of geometrical, quantum and collection terms, which are respectively the fraction of total area that is covered by the active photocathodes of the detectors, the efficiency of the photocathode to convert an incident photon into a photoelectron, and the probability that the photoelectron produces a detectable signal in the detector. A value of 73% is assumed for the geometrical efficiency in the baseline design [1], whilst the quantum efficiency is taken to be that of a typical bialkali photocathode (with average value of $\sim 20\%$ over a photon energy range 2–5 eV) and the collection efficiency is assumed to be close to 100%.

Two technologies are candidates for meeting these requirements, the hybrid photodiode (HPD) and the multianode photomultiplier (MPM). Commercially-available examples exist for both: for example a 61-pixel HPD from DEP, and a 64-cell MPM from Hamamatsu. Both satisfy the requirement of high spatial granularity, but fail to meet the desired geometrical efficiency, with a coverage of less than 50%. A vigorous programme of R&D is underway to develop an HPD with greater coverage, by moving to larger tubes [2]. However, for the MPM enlarging the tube is technologically difficult, and the use of electrostatic focusing to increase the coverage leads to a compensating reduction in the collection efficiency [3]. An alternative approach is to use a lens system in front of the detector, as a “light collector” to direct the incident light into the active part of the detector.

Such a lens system has been adopted by the HERA-B collaboration for use with MPM’s in the instrumentation of their RICH detector [4]. They use a pair of lenses in front of each MPM unit: a square plano-convex field lens followed by a biconvex collector lens, with an overall linear demagnification factor of 0.5. The lenses are moulded from UV-transmitting plastic, with refractive index $n = 1.5$. This solution is not ideal for LHCb, as the smallest available MPM cells are $2\text{ mm} \times 2\text{ mm}$, and with the HERA-B demagnification factor the effective photodetector granularity would be too large. Furthermore, the twin-lens arrangement gives unacceptable distortion if the photon angle of incidence exceeds 150 mrad. For the HERA-B detector (with C_4F_{10} gas radiator) the incidence angles are less than this limit, but an aerogel radiator will be used in LHCb with Cherenkov angle 240 mrad, so the limit will certainly be exceeded.² Finally, the four additional lens/gas interfaces that are introduced by the twin-lens arrangement will lead to substantial reflection losses (estimated as $\sim 15\%$ in total [4]).

An alternative lens system has therefore been developed, suitable for use with multi-anode photomultipliers in the LHCb RICH system.

²As shown in Section 3, the angled mirrors and detector planes of the LHCb RICH detectors lead to typically a 400 mrad angle of incidence of the photon on the detector plane, in the horizontal projection.

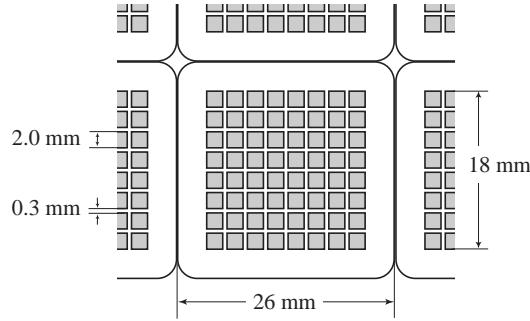


Figure 1: Dimensions of the Hamamatsu R5900–M64 tube, seen from the front; the active cells are shaded, and close-packing with other tubes is illustrated.

2 Proposed system

The proposed photodetector system involves close-packing MPM’s to cover the detector planes. The R5900–M64 tube from Hamamatsu is used, with an 8×8 square array of $2 \text{ mm} \times 2 \text{ mm}$ cells, as illustrated in Fig. 1. The current version of the tube has a slightly larger outer dimension than that shown in the figure, due to a vacuum-sealing flange, but this should be removed in the next version [3]. To give optimal coverage the lens system should demagnify the full $26 \text{ mm} \times 26 \text{ mm}$ area of the tube down to the $18 \text{ mm} \times 18 \text{ mm}$ photocathode area, i.e. a linear demagnification of 0.7. This will give an effective photodetector granularity of $2.8 \text{ mm} \times 2.8 \text{ mm}$, not far from the baseline requirement.

Without a lens system, the geometrical efficiency would only be 48%, given the photocathode area. In addition there is a loss of collection efficiency from the gap between cells, of 0.3 mm width. Assuming that the full 2 mm width of the cell is active and the region between the cells is inactive, this leads to a collection efficiency of 78% (within the photocathode area), which is not far from the estimated value (of 75%) for these tubes [3], and is also consistent with the results of a light-spot scan over the cells of a tube [5]. With the lens system described here, the first geometrical factor is almost fully recovered, but the second (22% inefficiency) will remain.

To reduce reflection loss compared to the HERA-B solution, a lens arrangement using a single lens in front of the MPM was investigated. In the thin-lens approximation, a single refracting surface of radius-of-curvature R has focal length

$$f = \frac{R}{1 - 1/n} ,$$

which, for refractive index $n = 1.5$, gives $f = 3R$. This provides just the required demagnification, if the distance d of the refracting surface from the photocathode plane is chosen to be equal to the radius-of-curvature, $d = R$, as illustrated in Fig. 2. Then the demagnification factor is $(f-d)/f \approx 2/3$. The conceptual design thus involves just a single refracting surface, with the other surface of the lens being flat (in optical contact with the MPM input window). This results in no extra lens/gas interfaces being introduced,

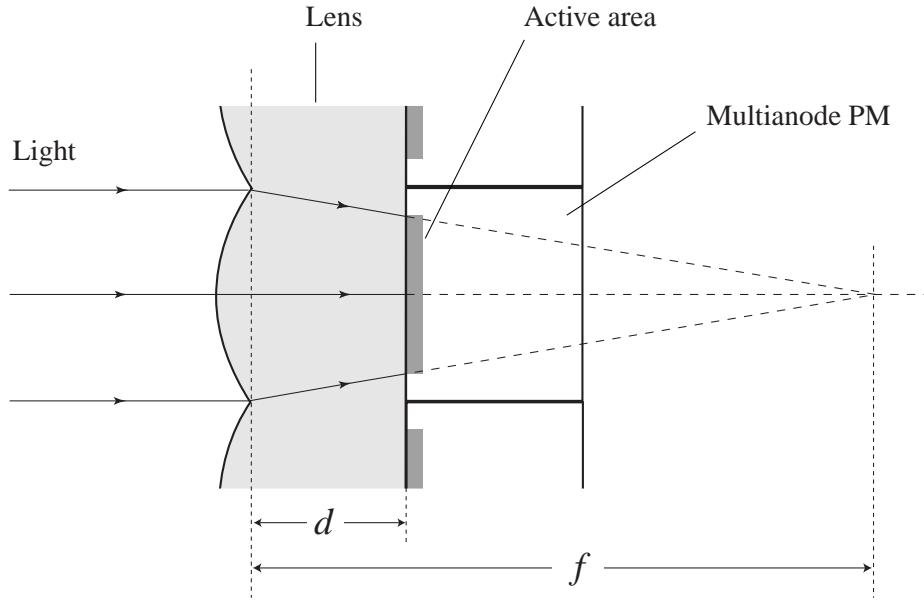


Figure 2: Schematic view of the lens system, in front of the close-packed multianode photomultipliers (seen from the side). The focusing of normally-incident light is illustrated.

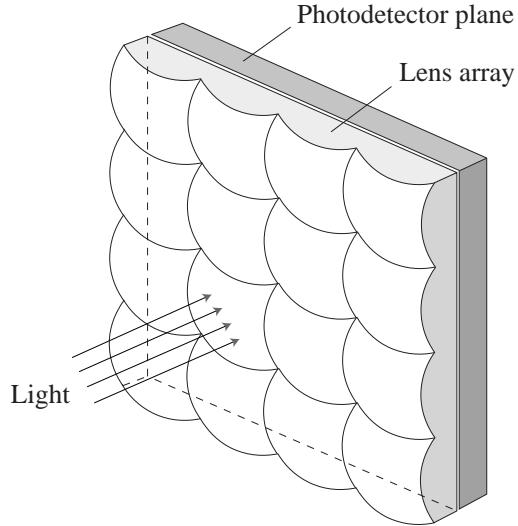


Figure 3: Isometric view of the lens array, mounted in front of the photodetector plane.

compared to the bare tube, and thus no penalty from reflection loss (assuming that the indices of refraction of the lens and the MPM entrance window are similar, as expected). Given that cheap, high-quality, UV-transmitting plastic lenses can be formed by injection moulding,³ neighbouring lenses could be moulded as a single unit, as illustrated in Fig. 3, with the number of lenses in the array limited only by manufacturing constraints. Such an array of lenses could be used to form the window that is foreseen to decouple the photodetectors from the Cherenkov radiator gas [1], further reducing losses.

³For example, by Wahl Kunststoffoptik GmbH, Triptis.

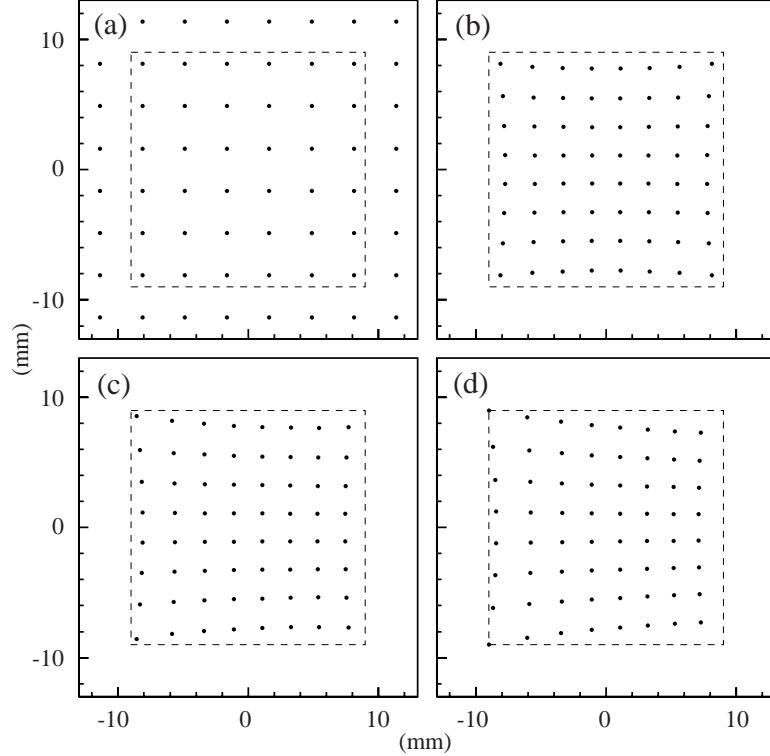


Figure 4: Impact points of a bundle of light rays on the entrance window of a multianode photomultiplier: (a) with no lens, (b–d) placing a 2cm radius-of-curvature lens in front of the detector plane; (b) is for normally-incident rays, (c) and (d) for a horizontal angle of incidence of 200 mrad and 400 mrad respectively. The dashed line indicates the active area of the tube.

The radius-of-curvature of the lens is a free parameter in this focusing solution, although it must of course exceed the distance from centre to corner of the MPM tube, $\sqrt{2} \times 13 \text{ mm} = 18.4 \text{ mm}$. The choice is a compromise between limiting distortion (due to corrections to the thin-lens approximation, for small radii) and limiting absorptive losses in the lens material (significant for large radii). In fact, the imperfect focusing of a low-radius lens is not a serious problem in this application, due to the relatively large cell size of the MPM—a photon need not be brought to a perfect focus, as long as it falls into the correct cell. A radius of 20 mm has been chosen for the implementation described here, giving a lens thickness that varies between 20 mm at the centre and 8 mm at the corners.

The demagnification that results from this lens configuration is illustrated in Fig. 4. As can be seen, for normally-incident light the required demagnification is achieved, with some slight pin-cushion distortion. This could in principle be corrected using an aspherical lens; that would lead, however, to increased distortion for light that is not normally-incident: with a spherical refracting surface, the focusing is largely independent of the angle of incidence. This can be seen in Fig. 4 (c) and (d), where the effect of large angles of incidence up to 400 mrad is only a slight shift of the impact point of the light on the

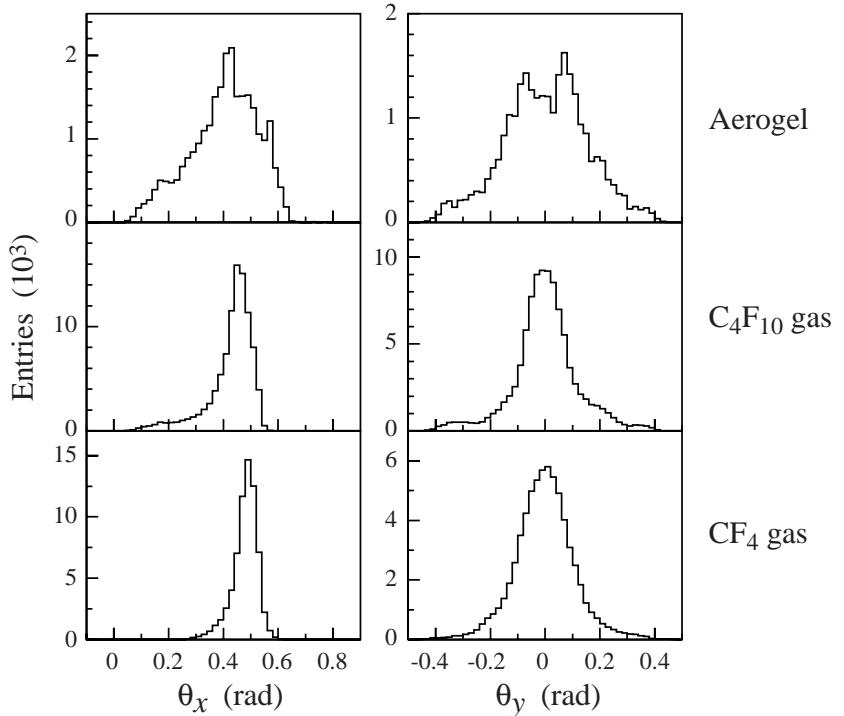


Figure 5: Angle of incidence of photons arriving at the detector planes of the LHCb RICH system, from fully-simulated b events. The angle θ_x (θ_y) is that between the photon and the horizontal (vertical) plane that contains the normal to the detector surface. The three rows are for the different Cherenkov radiators.

detector plane. This contrasts markedly with the HERA-B lens arrangement, which fails to accommodate such large angles of incidence: the important difference is the use of a single refracting surface.

3 Implementation in LHCb

The performance of a lens array of the type described in the previous section has been simulated for the RICH detector system of LHCb. That comprises two detectors, the first combining aerogel and C_4F_{10} gas radiators and the second using CF_4 gas [1]. Both devices are split into two halves either side of the beam pipe, with focusing mirrors tilted to left and right relative to the beam axis in order to bring their image planes out of the acceptance of the LHCb spectrometer. Cherenkov light produced in fully-simulated b-events has been ray-traced to the photodetector planes, and gives the distributions of incidence angle in the horizontal and vertical projections shown in Fig. 5. The distributions are remarkably similar for the three radiators, despite the large difference in Cherenkov angles (from 32 mrad for the CF_4 to 242 mrad for the aerogel, for high-momentum tracks). The distributions are broader for the aerogel than the gas radiators (with RMS of about 140 mrad and 100 mrad, respectively), but their width is determined not only by the

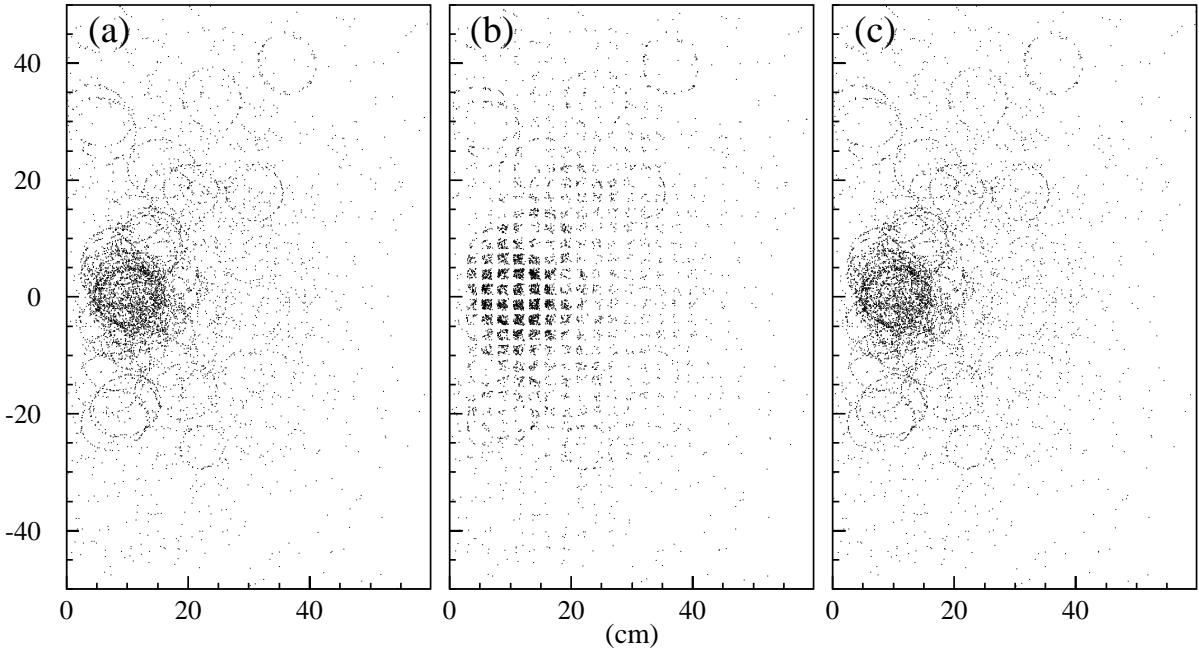


Figure 6: Photon impact points on a detector plane of the first LHCb RICH detector for 10 superimposed b events, (a) without lenses, (b) with the lens array, (c) after correction for the lens demagnification.

Cherenkov angle, but also by the distribution of angles for the tracks that produce the light. In the horizontal projection, the effect of the tilted focusing mirrors and detector planes is seen as an offset of about 400 mrad, whilst in the vertical projection the distributions are centred on zero.

The effect of including the lens array is illustrated in Fig. 6, which shows the photon impact points on one detector plane of the first RICH detector, for 20 superimposed events. In Fig. 6 (a) the hit pattern is shown with no lens array present. When the array is introduced, in Fig. 6 (b), the impact points are translated so that they almost all lie within the regions that would be covered by the active area of the MPM's. The transverse distance (horizontal and vertical) from the photon impact point to the centre of the lens that it passed through is shown in Fig. 7, for photons from the three different radiators. As can be seen, almost all of the photons lie within an $18 \text{ mm} \times 18 \text{ mm}$ region (indicated by the dashed lines), as desired. Only 4% fall outside this active region, a loss that could be reduced with the use of a larger radius-of-curvature lens (but that would lead in turn to increased absorptive loss). Also noticeable is the offset of the distribution in the horizontal coordinate, by about 3 mm, due to the 400 mrad average angle of incidence in that projection that was seen in Fig. 5. This offset is simply corrected by suitably aligning the lens array relative to the plane of close-packed MPM's.⁴

Taking the photon impact points from Fig. 6 (b) and scaling their distance from the

⁴However, the existence of such an offset does prevent the lens arrangement presented here from being simply integrated into the tube design (although that could be done for applications where the light is predominantly of normal incidence).

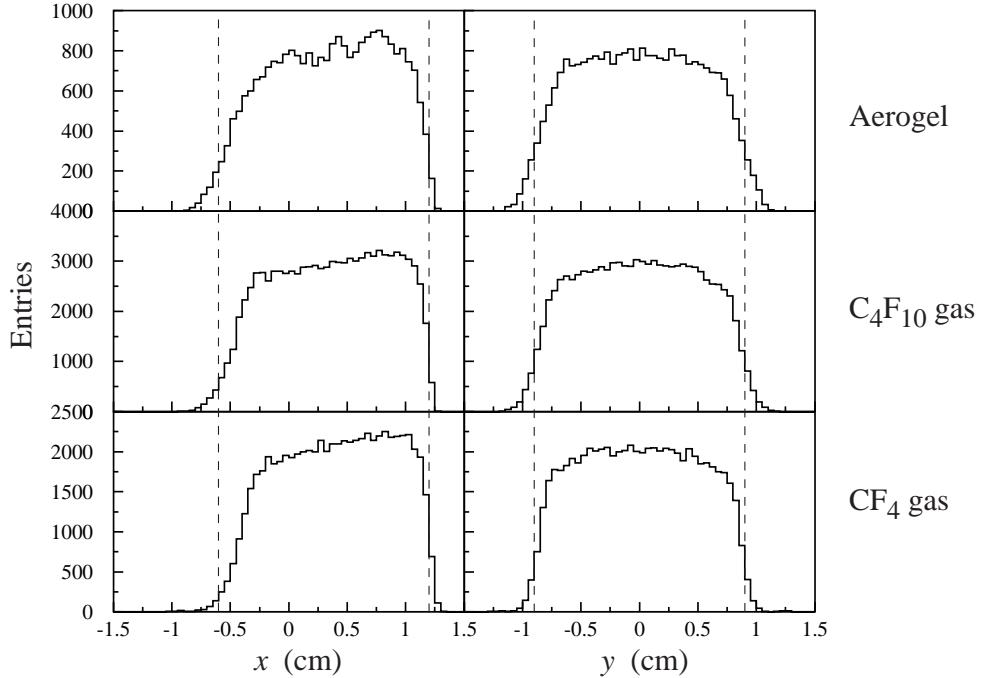


Figure 7: Transverse distance of the photon impact points on the LHCb RICH detector planes, relative to the centre of the lens that the photon passed through, in the horizontal (left column) and vertical (right column) coordinates. The dashed lines indicate the active area of the multianode photomultiplier.

centre of the tube that they fall into by the inverse of the demagnification factor (~ 1.4), the resulting hit pattern is shown in Fig. 6 (c). This corresponds to correcting for the demagnification of the lenses under the assumption of perfect optics, and no significant distortion is visible relative to the original pattern in Fig. 6 (a). The difference between the corrected and original impact coordinates (horizontal and vertical) is shown for photons from the three radiators in Fig. 8. The RMS widths of the distributions lie between $400 \mu\text{m}$ and $500 \mu\text{m}$. This is small compared to the effective photodetector granularity of 2.8 mm , and is also small compared to the pixellization component of the resolution that follows from that granularity, $2800/\sqrt{12} = 800 \mu\text{m}$. Thus the effect of the lens system on the resolution will not be significant.

4 Comparison with HPD's

Equipped with these lenses, the multianode photomultiplier becomes a viable alternative to the HPD's under development for photon detection in the LHCb RICH system. 4300 MPM's would be required to cover the total detector plane area of 2.9 m^2 . The nearly complete geometrical coverage gives an advantage over the HPD's, which are cylindrical and therefore lose 10% coverage from hexagonal close-packing; their target geometrical

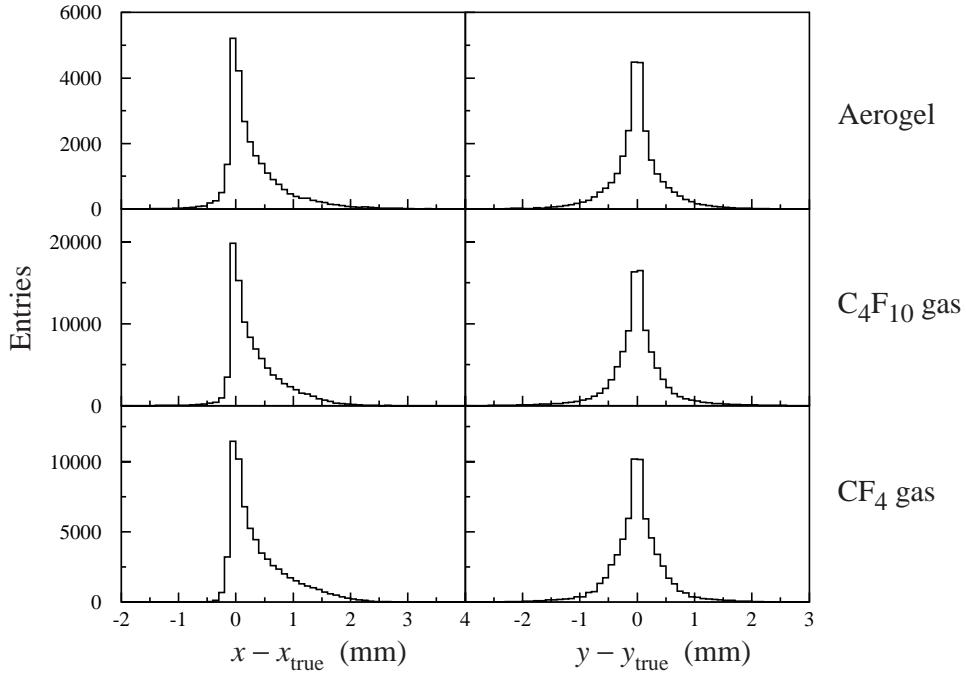


Figure 8: Difference between the coordinates of the photon impact point on the detector plane of the LHCb RICH system, with and without the lens array present. The coordinates with the lenses present have been corrected assuming perfect focusing.

efficiency is around 73%.⁵ This gain should counter the lower collection efficiency of the MPM (78% if calculated from the gaps between pixels, although a test-beam measurement of a single MPM example indicated a rather lower value [5]; the collection efficiency of the HPD is expected to be close to 100%). Thus the detected photoelectron yield is expected to be similar for the two devices.

A nice feature of the HPD is its excellent energy resolution, allowing single- and double-photoelectron signals to be cleanly resolved, which is not the case for the MPM. However, for the low occupancy expected in the LHCb RICH system of about 1%, this is not important. A disadvantage of the HPD is backscattering from the silicon detector (expected at the 20% level) which, depending on the focusing scheme that is adopted, could lower the detection efficiency and give correlated noise in nearby pixels. HPD's are also sensitive to stray magnetic fields, with significant image distortion for fields of a few gauss, whilst the MPM is expected to be relatively insensitive to magnetic fields below 100 gauss. The HPD has low gain, ~ 5000 , and therefore suffers from problems of low signal-to-noise; this requires electronics to be mounted inside the vacuum envelope, which may give problems with vacuum compatibility and heat dissipation. The MPM has a large gain of $\sim 10^6$, simplifying the read-out electronics (which can be connected straightforwardly to a socket, outside the vacuum). It also only requires a high voltage of

⁵In principle a similar lens arrangement could be used to increase the coverage of small-diameter HPD's; however, for the large tubes under development the thickness of the lens would be prohibitive.

1 kV, compared to \sim 20 kV for the HPD.

In addition there is the issue of the potentially serious background from Cherenkov light produced in the photodetector entrance window by tracks that pass through the window. There are estimated to be of order 10 such tracks on average per event (through the total photodetector area) [6]. The number of photons produced is large enough that, after internal reflection in the window, photoelectrons can be produced at some distance from the track impact point. This background requires further study, and may be controllable by accurate timing of the signals (requiring a few ns precision) or by segmenting the entrance windows. However, if the information from the whole photodetector unit has to be discarded for each such track, then it is clearly advantageous to have small units: 10 MPM's correspond to only 0.2% of the detector plane, whilst for the large HPD's this could be as much as 5%.⁶

Finally there is the question of cost. The projected cost of the HPD's under development is 10 CHF/channel (or even less). The current price of an R5900-M64 multianode photomultiplier tube corresponds to over 40 CHF/channel. It is foreseen that the price will drop to 20 CHF/channel, at which point the total photodetector cost would be 5.5 MCHF, still rather higher than the sum budgeted. (The cost of the lenses would be negligible in comparison, a few francs each; the external electronics has also not been included in this cost). For this reason the MPM is currently considered to be a back-up solution, in case the HPD R&D programme fails. If the cost could be further reduced, then with the advantages listed above, they would become a serious competitor for photodetection in the LHCb RICH system.

5 Conclusion

A lens system has been presented that doubles the geometrical coverage of multianode photomultipliers to 96%, for a realistic simulation of an implementation in the RICH system of LHCb. The effective photodetector granularity is increased from 2.0 mm \times 2.0 mm to 2.8 mm \times 2.8 mm by the lenses, but the effect on the resolution of imperfect focusing has been shown to be small. The lens array could be formed from injection-moulded UV-transmitting plastic, and could also serve to isolate the photodetectors from the Cherenkov radiator gas.

The performance of such an array of lens-equipped MPM's would match that projected for the large-scale HPD's under development, and could in some respects be superior; the main drawback is currently their high cost. Work will continue to test such a lens arrangement in the laboratory.

⁶Note that for the MPM's care must be taken that light produced in the lens array does not pollute the neighbouring tubes: this may preclude the moulding of a large number of lenses as a single unit.

Acknowledgements

This work was inspired by the studies for HERA-B, reported by Jerry Rosen and Daniel Broemmelsiek. It is also a pleasure to thank Tom Ypsilantis for discussions, and for pointing out that a similar lens arrangement has been developed elsewhere for a very different application [7].

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