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Angular acceptance of lens based light collection systems for an upgrade of the Belle PID system

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Abstract

The report reviews the present experience in lens based light collection systems for Čerenkov counters with an emphasis on acceptance for photons with large angles of incidence.

1 Introduction

As possible options of a upgrade of the particle identification system of the Belle spectrometer two devices are being discussed which could partially replace the existing aerogel threshold counter [1]. One of them is a proximity focussed aerogel Čerenkov counter [2], which would cover the forward direction. The other is a time-of-propagation counter [3, 4, 5], which would cover the barrel region. Both would be equipped with a vacuum based photon detector, able to efficiently detect single photons in high magnetic field. While such a detector is still being developed [2, 5], it is quite probable that its active area will only be a fraction of the full area of the photon detector (as e.g. 25% for multianode PMTs as used in the HERA-B RICH [6], or 40% as proposed for the LHCb RICH [7]). Since the expected number of photons is low, a light collection system will be necessary to increase the fraction of the active area. The particular feature is in this case the need for large angular acceptance of such a light collection device.

In the present report possibilities are discussed how to increase the active area, with some emphasis on the solutions which can be applied immediately with existing equipment in on-the-bench tests with cosmic rays.

2 Matrix formalism

We shall first assume that our light collection system can be well described as a system of thin lenses. We shall describe a ray as a set of two vectors,

$$\begin{pmatrix} x \\ x' \end{pmatrix}$$

one for each of the projections perpendicular to the optical axis z. To arrive at the tranformation matrix M which relates the position and direction of a light ray before and after the lens, we first note that a ray which is parallel to the optical axis, intersects the axis at point $z = f$ after the lens, so that

$$M_L \begin{pmatrix} x_0 \\ 0 \end{pmatrix} = \begin{pmatrix} x_0 \\ -\frac{x_0}{f} \end{pmatrix},$$

while the central ray passes the lens uperturbed,

$$M_L \begin{pmatrix} 0 \\ x'_0 \end{pmatrix} = \begin{pmatrix} 0 \\ x'_0 \end{pmatrix}.$$

From the two requirements it is easy to derive the form for M_L,

$$M_L = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} \tag{1}$$

In a similar way the transformation matrix M_D for the drift space of length d can be derived,

$$M_D = \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix} \tag{2}$$

With these two matrices, we can well model most lens based light collection systems.

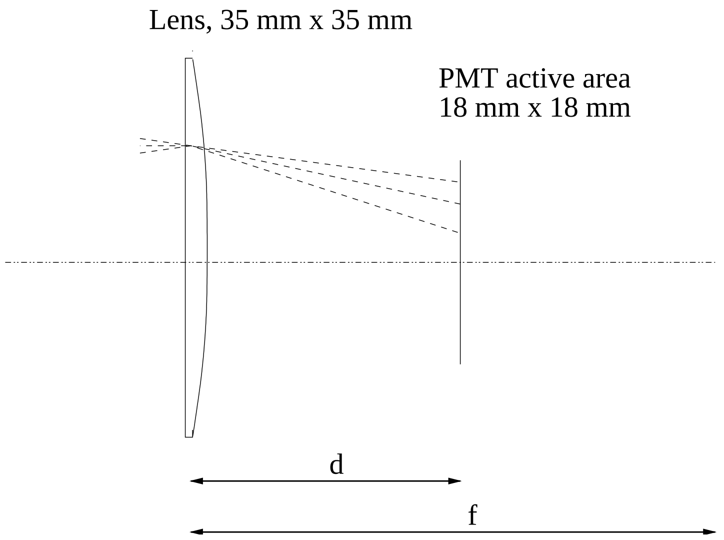

Figure 1: *Single lens light collection system. The parameters of the system are the size of the lens s_0 (in this case 35 mm), focal length f of the lens, and the distance d between the lens and the PMT. Indicated are light rays for the case of perpendicular incidence and* ± 100 *mrad.*

3 Single lens

The overall transformation matrix T is in this case a product of the lens and drift space matrices,

$$T = \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} = \begin{pmatrix} 1 - \frac{d}{f} & d \\ -\frac{1}{f} & 1 \end{pmatrix} \tag{3}$$

Thus

$$x_1 = x_0(1 - \frac{d}{f}) + x_0' d \tag{4}$$

If we require a magnification by c (say 1/2), $x_1 = cx_0$, it is easy to see that for perpendicularly incident rays ($x_0' = 0$),

$$\frac{d}{f} = 1 - c. \tag{5}$$

The variation of image position on the angle of incidence is, however, of considerable importance, and essentially limits the geometrical acceptance.

In Figs. 2 and 3 a set of plots is shown with the angular dependence of geometrical acceptance of such a system for some typical choices of dimensions. The geometrical acceptance was determined by tracing a matrix of 100x100 parallel rays trough the system.

The choice of geometrical parameters is motivated in the following way. The PMT pitch of 36 mm is the same as in the case of HERA-B RICH, the focal length of 95 mm is the focal length the plan-convex lens of the HERA-B RICH, and 48 mm is the focal length of a closely packed pair of such lenses [8]. The smaller pitch of 26 mm is the one chosen

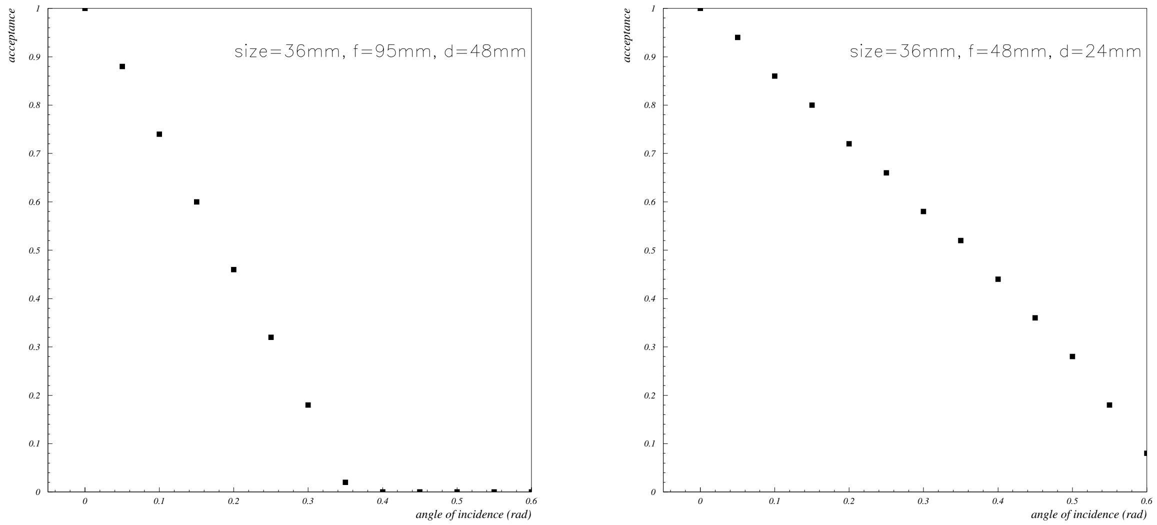

Figure 2: *Angular acceptance of a thin lens as determined by using the tranformation matrix (Eq. 3) A square of 36 mm side is imaged on a 18 mm side square PMT active area by using lenses of focal length 95 mm (left) and 48 mm (right). No reflection and absorption losses were taken into account.*

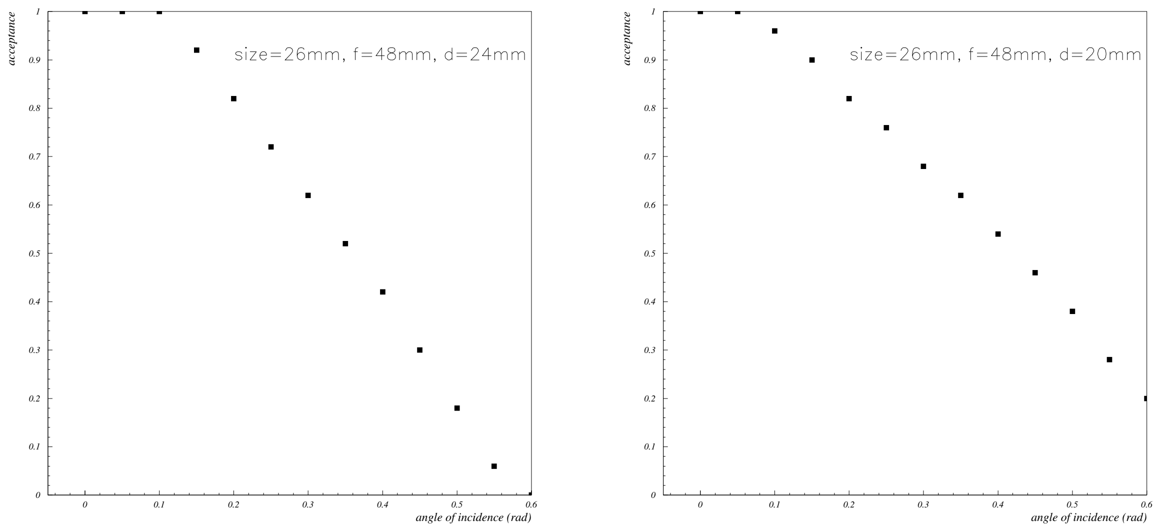

Figure 3: *Same as Fig. 2, except that a square of 26 mm side is imaged on a 18 mm side square PMT active area by using lenses of focal length 48 mm, at two lens-PMT distances of 24 mm (left) and 20 mm (right).*

by LHCb [7], and became possible with an upgrade of Hamamatsu R5900 multinanode PMT production technique, resulting in a PMT case of smaller dimensions.

4 Two lens system

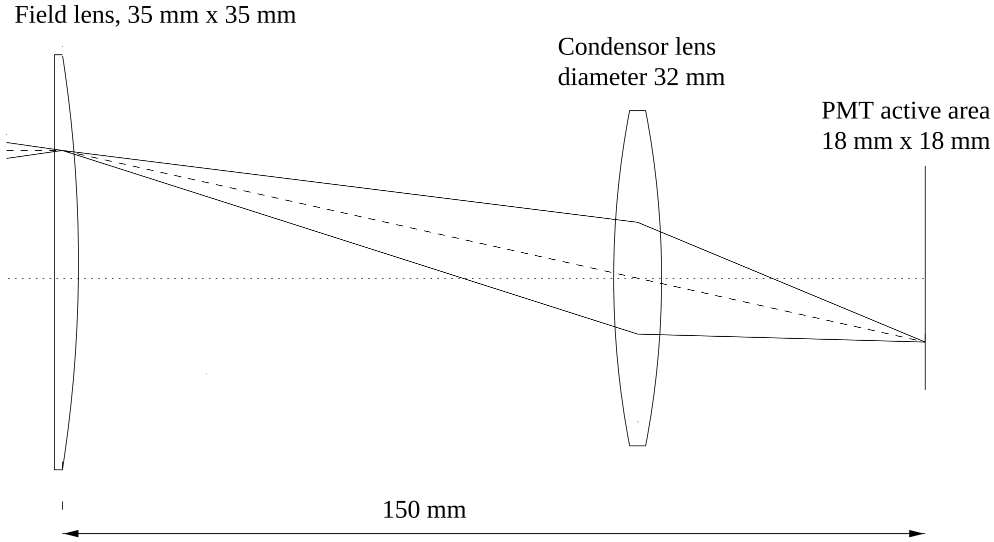

Figure 4: *A system of two lenses. The geometrical parameters are as in the case of the HERA-B RICH: the first lens is a square of side* $s_0 = 35$ *mm, and the second a circle with a diameter of* $2r_1 = 32$ *mm.*

The transformation matrix T is in this case a product of two lens and drift space matrices,

$$T = T_1 T_2 = \begin{pmatrix} 1-\frac{d_2}{f_2} & d_2 \\ -\frac{1}{f_2} & 1 \end{pmatrix} \begin{pmatrix} 1-\frac{d_1}{f_1} & d_1 \\ -\frac{1}{f_1} & 1 \end{pmatrix} = \begin{pmatrix} (1-\frac{d_2}{f_2})(1-\frac{d_1}{f_1}) - \frac{d_2}{f_1} & d_1(1-\frac{d_2}{f_2}) + d_2 \\ -\frac{1}{f_2}(1-\frac{d_1}{f_1}) - \frac{1}{f_1} & 1-\frac{d_1}{f_2} \end{pmatrix} \tag{6}$$

What do we require of this system? First, we need a magnification of $-c$, say typically $c = 1/2$. We would also like to have a system where the direction of the photon at the first lens has no (or little) influence on the position on the photon detector surface. This is actually not important for the reconstruction of photon path since for a given hit-track combination the relation is unambiguous, but rather because of possible acceptance losses. If we namely set the demagnification such that for normally incident rays the front surface is imaged on the active surface of the photon detector, a variation of image position with variing angle of incidence immediately reduces the acceptance.

These two conditions can be translated into equations by noting that by the above transformation matrix the position on the photon detector plane is given by

$$x_2 = (1 - \frac{d_2}{f_2} - \frac{d_1}{f_1} + \frac{d_1}{f_1}\frac{d_2}{f_2})x_0 + (d_1 + d_2 - \frac{d_1 d_2}{f_2})x_0' \tag{7}$$

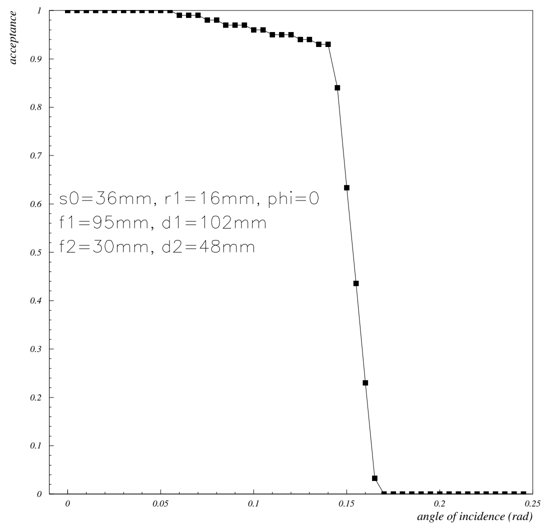

Figure 5: *Angular acceptance of the HERA-B two lens system as determined by using the transformation matrix. No reflection and absorption losses were taken into account.*

The two requirements translate into

$$(1 - \tfrac{d_2}{f_2} - \tfrac{d_1}{f_1} + \tfrac{d_1}{f_1}\tfrac{d_2}{f_2}) = -c \tag{8}$$

and

$$(d_1 + d_2 - \tfrac{d_1 d_2}{f_2}) = 0 \tag{9}$$

Dividing the second equation by f_1 and summing the two, we arrive at

$$1 - \frac{d_2}{f_2} = -c \tag{10}$$

from where

$$\tfrac{d_2}{d_1} = c \tag{11}$$

and

$$\tfrac{d_2}{f_2} = 1 + c \tag{12}$$

while $\frac{d_1}{f_1}$ is still free. We will choose

$$\frac{d_1}{f_1} = 1, \tag{13}$$

i.e. the second lens is positioned at the focal point of the first one. We note that in this case the matrix T becomes particularly simple,

$$T = \begin{pmatrix} -\frac{d_2}{f_1} & d_1(1 - \frac{d_2}{f_2}) + d_2 \\ -\frac{1}{f_1} & 1 - \frac{d_1}{f_2} \end{pmatrix} \tag{14}$$

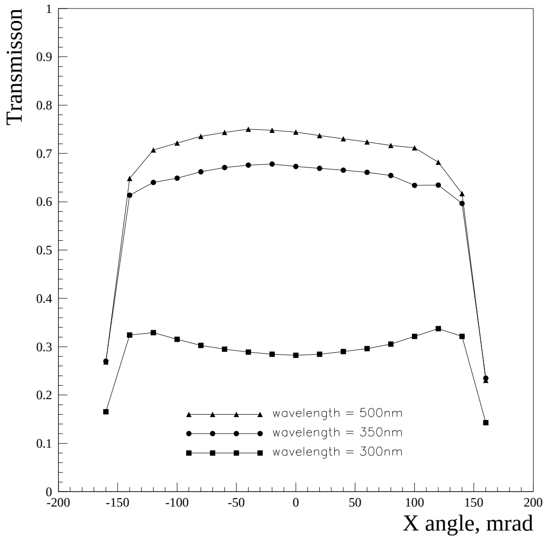

Figure 6: *Measured angular acceptance of the HERA-B two lens system [8].*

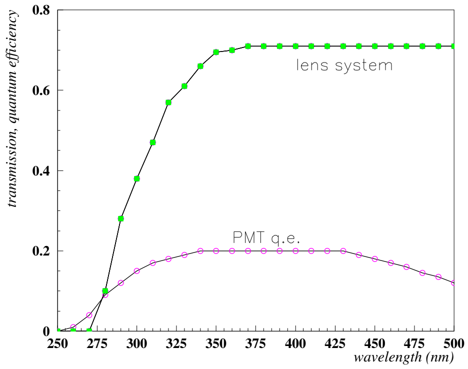

Figure 7: *Measured transmission of the two lens system for normally incident photons, plotted as a function of wavelength [8]. Also shown is the quantum efficiency of the multianode PMT Hamamatsu R5900.*

We note that the geometrical acceptance of such a system is limited due to the fact that for large angles of incidence the refracted rays miss the second lens (Fig. 4). The size of the second lens cannot be increased at will, since the second lens cannot exceed in size the first one, $2r_1 < s_0$. This roughly limits the angular acceptance to $\theta < r_1/f$ as can be easily deduced from Fig. 4.

The acceptance (Fig. 5) was again estimated by tracing a 100x100 light ray matrix through the system. The sharp drop around 150 mrad is in agreement with the rough estimate discussed above. By comparing the calculated acceptance with the measured one (Fig. 6) we first note that the principal feature, the cut off at 150 mrad, is well reproduced. We observe, however, that in addition to the reflective losses at four boundaries (8%), the bulk absorption plays a sizeable role. This becomes of importance in particular at lower wavelengths, as can be seen in Fig. 7.

5 Single thick lens

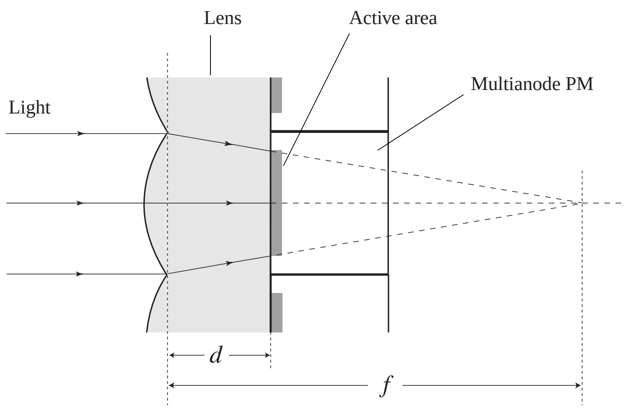

Figure 8: Light concentrator for one of the LHCb photon detector options, a single lens with a multianode PMT.

In the case of the LHCb RICH [7], in one of the photon detector options lenses are considered in combination with multianode PMTs at 26 mm pitch. In this case a single thick lens was chosen [9] as the optimal choice. Since the lens radius of curvature (25 mm) is comparable to its lateral dimensions (26 mm), the thin lens approximation cannot be applied. In this case the 100x100 ray matrix was propagated by exact ray tracing.

For large angles od incidence the geometrical acceptance is again limited due to the shift of the image on the PMT plane, as can be seen in Fig. 9. By comparing with the isolated thin lens case, one has to take into account that in this case there is no 8% reflection loss at two lens surfaces. On the other hand, the larger thickness makes the bulk absorption even more important.

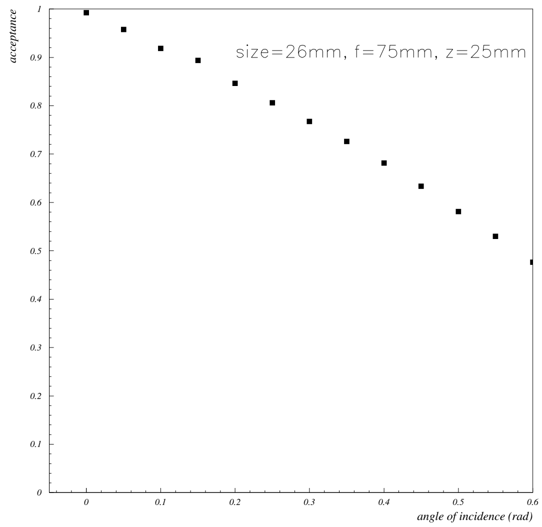

Figure 9: *Angular acceptance of the LHCb thick lens as determined by ray tracing. No absorption losses were taken into account.*

6 Influence of bulk absorption on light collection efficiency

To account for the influence of absorption losses on the lens system transmission, the absorption curves provided by one of the plastic lens manufacturers (WAHL), and cross-checked by test measurements for the HERA-B light collection system [10], were used. By comparing Figs. 10 and 11 we conclude that at the same pitch (26 mm) the thick LHCb like lens is better at high wavelengths (little absorption) due to the absence of the 8% reflection loss, but behaves worse at short wavelengths. We also note that if the lens cannot be optically coupled to the PMT window for safety reasons (in tha case of R5900 PMTs the photocathode at the entrance window is at high voltage), and additional 8% reflection loss has to be added, such that the thin lens would become the prefered choice.

We also observe (Fig. 12) that even with the existing HERA-B field lenses and the PMTs positioned at a 36 mm pitch, the light collection system has a reasonably good efficiency.

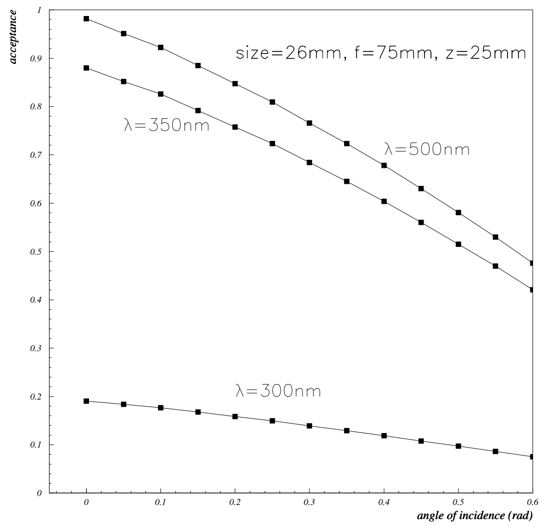

Figure 10: *Acceptance of the LHCb thick lens as determined by ray tracing by taking into account absorption in the lens material. The lens was assumed to be optically coupled to the PMT window, such that no reflection losses had to be considered.*

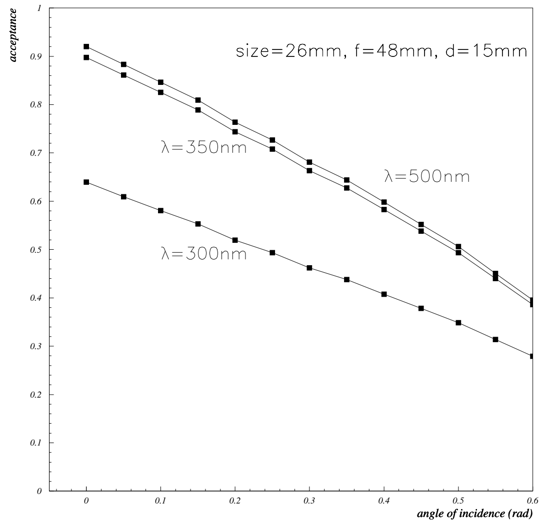

Figure 11: *Acceptance of a thin lens for the same pitch (26 mm) as in the case of the LHC thick lens, as determined by ray tracing by taking into account absorption and reflection losses.*

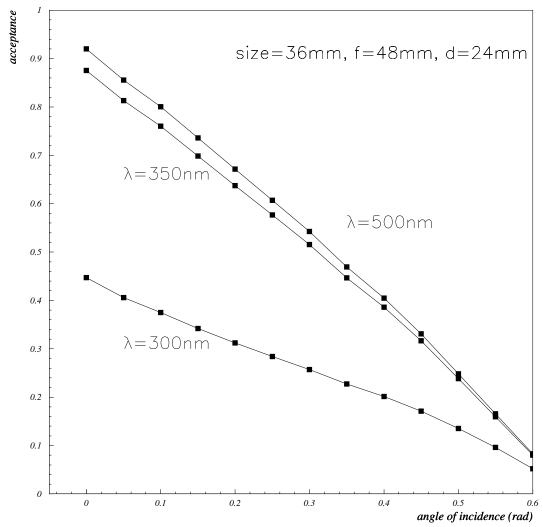

Figure 12: *Same as Fig. 11, for the pitch of 36 mm, by using a back-to-back coupled pair of HERA-B lenses.*

7 Use of a lens based light collection system in proximity focussed RICH counters

If a light collection system is used in a proximity focussed RICH counter, one has to take into account that charged particles will traverse it, and will radiate Čerenkov photons. In the case of a thick lens directly optically coupled to the PMT surface, most of the photons will reach the photocathode, and contribute considerably to the occupancy on the photon detector. In the thin lens version case there are two advantages. First the number of emitted photons in the lens is lower due to the difference in the path length of the particle in the radiator medium. In addition, a sizeable fraction of these background photons will get trapped in the lens since their angle of incidence upon the lens surface will exceed the total internal reflection angle. Those photons, which will exit the lens, will be refracted to very large angles, and can be absorbed before reaching a PMT if a black painted egg-crate like structure is used to separate PMT-lens units. Such an arrangement, which resembles the mechanics of the HERA-B light collection system, has an additional benefit: the egg-crate material can be chosen such that it provides additional shielding from the magnetic field.

To summarize, it seems that a single thin lens light collection system offers some advantages over other solutions, both as far the absorption and background sources are concerned, as well as by offering a possiblity to magnetically shield the PMTs. A 4x4 module shown in Fig. 13 could look very much like the solution which was proposed as one of the possibilities for the HERA-B light collection system [11]. Such a set-up could also soon be tested on the bench, since all the components are available, including the lenses, if for a single lens a pair of two HERA-B plan-convex 'field' lenses is used back to back.

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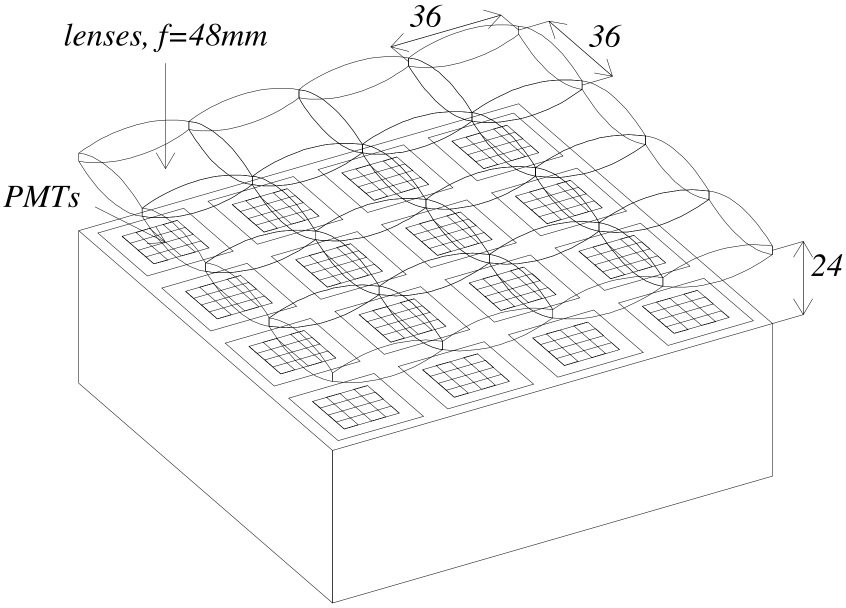

Figure 13: *A 4x4 PMT module with a single lens light collection system. For the sake of clarity the black painted egg-crate support structure for the lenses was not drawn.*