Recent Progress in Čerenkov Counters

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Abstract— **The paper reviews recent progress in individual components of Čerenkov counters, as well as the performance of installed detector systems.**

I. Introduction

Particle identification based on the determination of velocity by exploiting the Čerenkov effect has become in the last decade a standard tool in particle and nuclear physics. Much of the progress is either directly or indirectly connected to Tom Ypsilantis, who suddenly passed away during his work on several interesting new projects.

In the present contribution I will focus on some of the aspects of the research and development in this field. The interested reader will find further details in a recent overview [1], as well as in the proceedings of three conferences dedicated to the subject [2]-[4], with two excellent overview papers by Tom Ypsilantis and Jacques Seguinot [5].

A. Čerenkov counters

A charged track with velocity $v = \beta c$ above the speed of light c/n in a medium with the index of refraction n emits polarised light (Fig. 1) at a characteristic (Čerenkov) angle, $\cos\vartheta = 1/\beta n$.

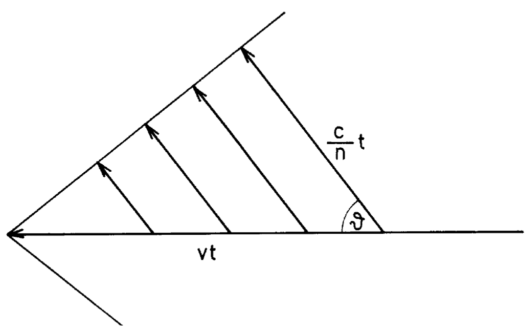

Fig. 1. Čerenkov effect.

If the particle is below threshold, $\beta < \beta_t = \frac{1}{n}$, no Čerenkov light is emitted. For particles above threshold the number of Čerenkov photons emitted over unit photon energy E in a radiator of length L amounts to

$$\frac{dN}{dE} = L\frac{\alpha}{\hbar c}\sin^2\vartheta \qquad (1)$$

where $\frac{\alpha}{\hbar c} = 370\mathrm{eV}^{-1}\mathrm{cm}^{-1}$. To give an example of the number of detected photons, we note that in 1 cm of water ($n = 1.33$) a track with $\beta = 1$ emits $N = 320$ photons in the spectral range of visible light ($\Delta E \approx 2$ eV). If Čerenkov photons were detected with an average detection efficiency of $\epsilon = 0.1$ over this interval, $N = 32$ photons would be measured.

In general, the number of detected photons is parametrised as

$$N = N_0 L \sin^2\vartheta, \qquad (2)$$

where N_0 is the figure of merit of a Čerenkov counter,

$$N_0 = \frac{\alpha}{\hbar c}\int Q \cdot T \cdot R \; dE \qquad (3)$$

and $Q \cdot T \cdot R$ is the product of photon detection efficiency, transmission of the radiator and windows and reflectivity of mirrors employed. Typically, N_0 is found to be between 50 and 100 cm^{-1}.

There are two types of Čerenkov counters. In a threshold counter photons are counted to separate particles below and above threshold. In a Ring Imaging Čerenkov (RICH or CRID) counter the Čerenkov angle is measured, together with the number of photons. The RICH technique which was proposed more than twenty years ago by Tom Ypsilantis and his coworkers, considerably boosted the particle identification capabilities of magnetic spectrometers.

Components of a Čerenkov counter (Fig. 2) are radiators, mirrors, windows, detectors of single photons with light collectors and auxiliary systems.

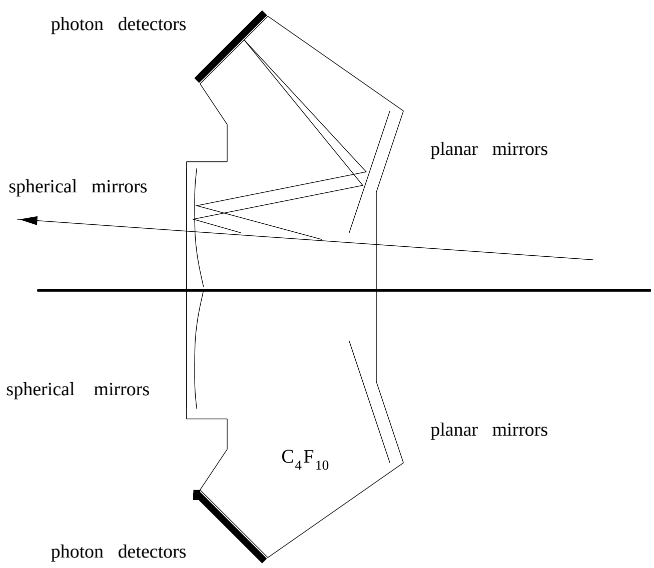

Fig. 2. Elements of a RICH counter. Shown is the HERA-B RICH layout, a typical fixed target example.

As it turns out, between 10 and 20 detected photons per track are needed for an adequate pattern recognition,

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depending on the density of tracks. This has to be supplemented by a good resolution in Čerenkov angle measurement for each individual photon. To arrive at this goal, one clearly has to design and build the counter very carefully and run it stably over extended periods of time.

B. Long term experience

Long term running experience, in particular from DELPHI [7] and SLD [8] ring imaging Čerenkov counters, has taught us several lessons. In particular, we have learned how to build a very sensitive detector, and operate it over many years [9] in spite of the fact that the light sensitive substance employed was a chemically highly aggressive TMAE [10] in a wire chamber. RICH counters proved to be a reliable tool for particle identification, of particular importance for b physics [11], [12]. In addition, detection of Čerenkov photons proved to be an essential tool in detection of neutrinos and high energy cosmic γ rays.

During the last decade it also became clear that the next generation of Čerenkov counters both at B factories and at the hadron machines requires new ideas. In some applications, e.g., high photon rates are expected, such that the known rapid aging of TMAE based photon detectors makes its use almost impossible [13], [14].

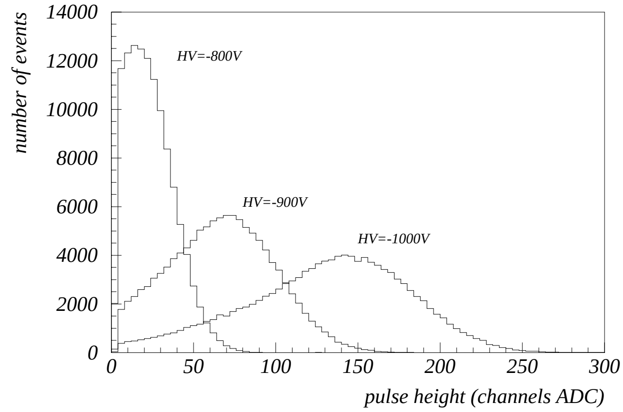
C. Recent developments

Considerable research and development improved the reliability and stability of Čerenkov counters and broadened their use. In this contribution I shall first review the progress of the most critical component, the detector of single photons. The performance will be discussed of multi-anode photomultiplier tubes, wire chambers with photosensitive substances TEA and CsI, and the novel hybrid photon detector HPD, as well as systems of lenses as light concentrators. A new technique, the DIRC at BaBar, will be presented, and the use of the aerogel radiator for Belle, HERMES and LHCb experiments. Finally, the performance of the HERA-B RICH will be presented as an example of a RICH that successfully operates at high track densities.

II. Photon detector progress

A. Multianode PMTs in HERA-B

One of the major drawbacks of conventional photomultiplier tubes if compared to wire chamber based photon detectors is poor granularity, which limits the achievable resolution in Čerenkov angle. This can in principle be improved in a multianode photomultiplier tube, if the tube has a capability to detect single photons with high efficiency, and little cross-talk among the channels. The HERA-B RICH collaboration [15] was the first to employ multianode photomultiplier tubes in a RICH counter (Fig. 2), after they have shown [16] that the tubes considered (Hamamatsu R5900, versions M16 and M4 with 16 and 4 square shaped channels, respectively) fulfil the above requirements (Fig. 3). A series of measurements was carried out to understand the single photon response of the full set of 2250 multianode photomultiplier tubes prior to the installation [16], [17]. The installed photon detector, which is build of units of four PMTs (Fig. 5), behaves very well even in a very hostile environment of a hadron machine, showing clear rings with very few noisy channels ($< 0.5\%$), as can be seen from Fig. 4 [18].



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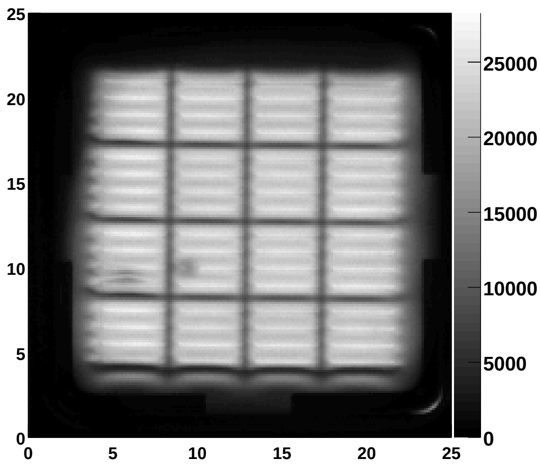


(b)

Fig. 3. Performance of the R5900-M16 photomultiplier tubes: pulse height distributions due to single photoelectrons, and the sensitivity of the surface when scanned by a light beam spot of about 30 μm in diameter, with scales in mm [16], [17].

B. Photon detector reborn: TEA for CLEO III RICH

TEA (Triethylamine) is a low vapour pressure, photosensitive additive to wire chamber gas with an absorption length of 0.6mm, and quantum efficiency as shown in Fig. 6. It is typically used in a thin multiwire chamber with pad read-out (Fig. 7). The substance was first used in the pioneering RICH experiment E605. Later it was considered as the RICH photon detector for B-factories, and a proximity focusing RICH (Fig. 8) prototype with integrated electronics was designed, built and tested by Tom Ypsilantis

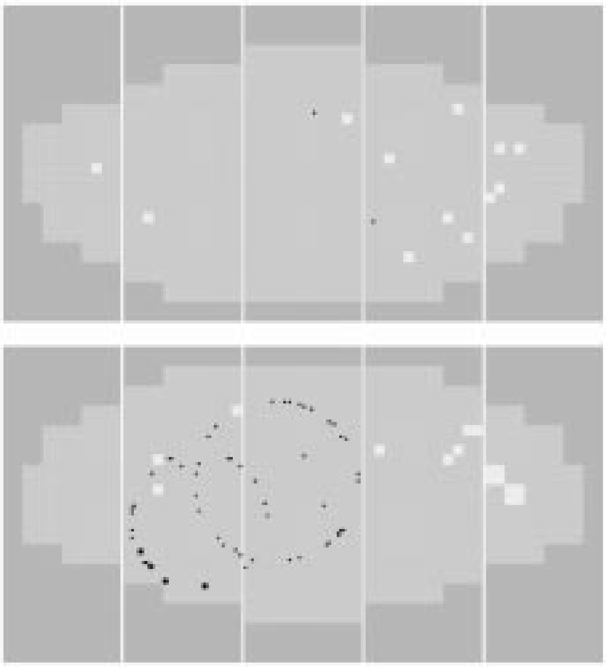


Fig. 4. A low multiplicity event recorded in the HERA-B RICH: on top of two clear rings on the lower photon detector half, only very few spurious hits can be observed. The diameter of the larger ring is about 60 cm.

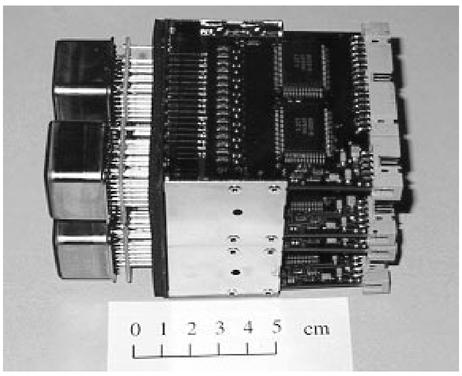


Fig. 5. Fully equipped basic module of the HERA-B RICH housing Hamamatsu R5900-M16 photomultiplier tubes.

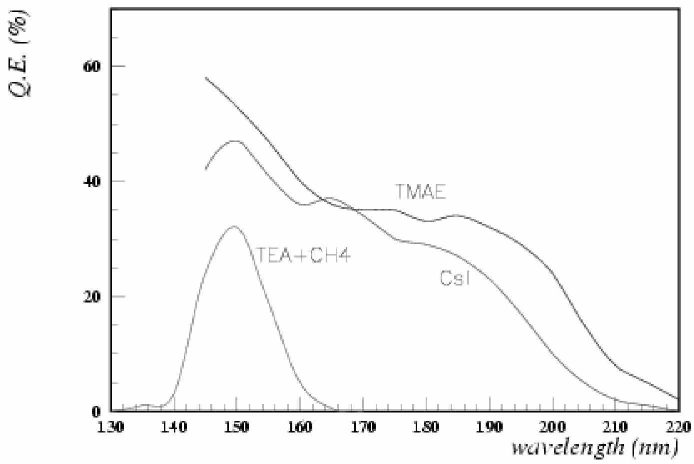


Fig. 6. Quantum efficiency of photosensitive substances which are most commonly used with wire chambers.

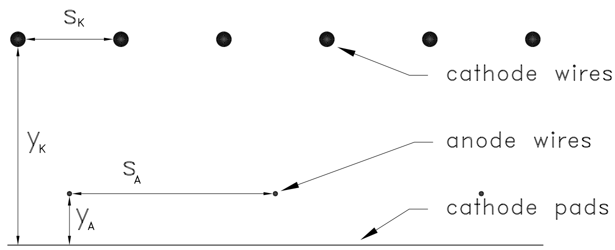


Fig. 7. An asymmetrical thin multiwire chamber with pad read-out and a photosensitive additive (either TEA in the chamber gas, or CsI evaporated on the pad cathode). The dimensions are: $s_K = 1$ mm, $y_K = 2$ mm, $s_A = 2$ mm, $y_A = 0.6 - 1$ mm. Instead of cathode wires, stripes evaporated on the chamber window material can be employed.

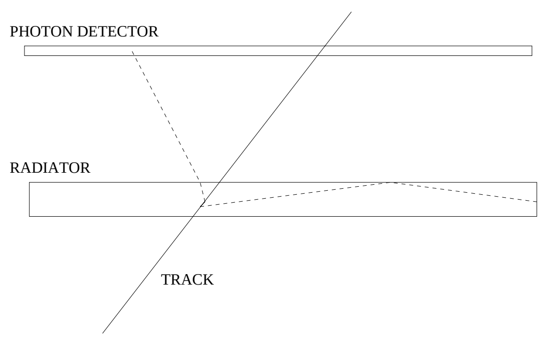
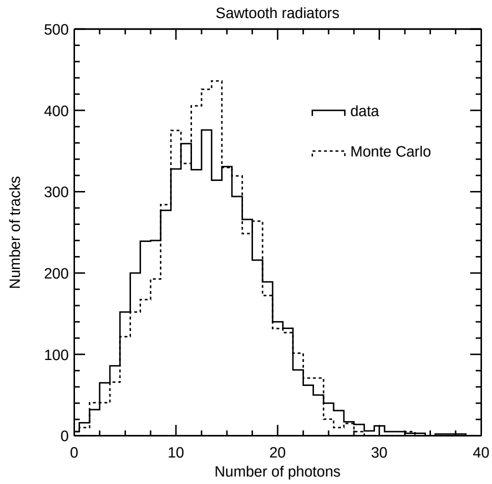


Fig. 8. Proximity focusing RICH: the Čerenkov photons are emitted in a thin (typically 1 cm thick) solid or liquid radiator medium, and are detected after they have traversed an gap of typically 10-20 cm.

and collaborators [19]. The concept was later adopted for the CLEO spectrometer, with an important modification of the solid LiF radiator in the detector region where high momentum particles cross the radiator plane perpendicularly . There a sawtooth form is used to reduce the loss of Čerenkov photons due to trapping in the radiator by total internal reflection [20]. The counter is presently under commissioning in the CLEO III detector. The preliminary results [21] are promising as can be seen from Fig. 9, in good agreement with design values.

C. Photon detector mature: CsI

It was again Tom Ypsilantis with coworkers [22] who pioneered yet another photo-sensitive detector: a multiwire chamber with a solid CsI layer, 100 nm - 1 μm thick, evaporated on the cathode plane with pads (Fig. 7). CsI has a similar response to light as TMAE (Fig. 6), and is known



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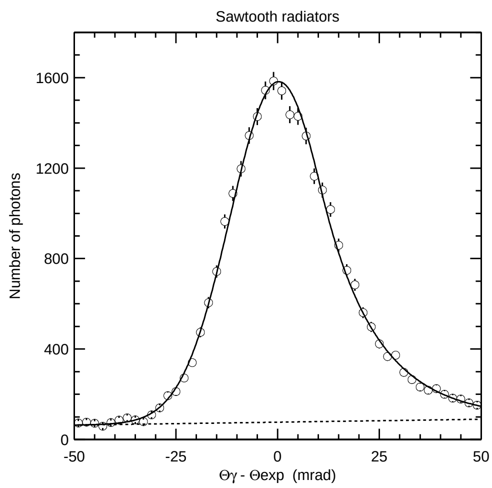


(b)

Fig. 9. Performance of the CLEO III RICH [21]: distribution of the number of detected photons (a), and the deviation of the single photon Čerenkov angle measurement from the nominal value, both for the sawtooth radiator region (b).

as a solar blind material for photomultiplier tubes. It was soon shown that such a counter allows for an efficient detection of Čerenkov photons [23]-[25], but its performance turned out to depend on several parameters (see review papers [26], [27]).

The material requires a high purity chamber gas, usually methane with water and oxygen content of order ppm, as well as careful handling of the evaporated cathodes. A lot of R&D (influence of substrate, conditioning, thickness, evaporation procedure, transfer to the chamber) was needed to make the technique mature [26]-[29]. The stability of the CsI photocathodes in a chamber was studied over several years with promising results (Fig. 10). The aging under ion bombardment, combined with high rate instabilities [30] makes it currently, however, less suitable for

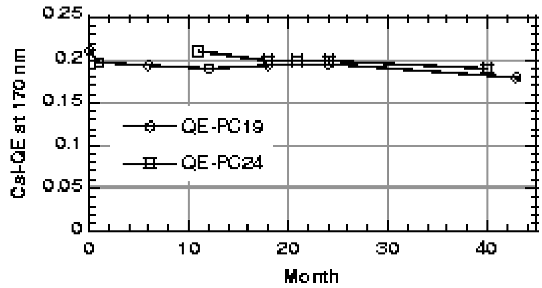


Fig. 10. Stability of CsI cathodes, stored in gas [28].

experiments such as HERA-B with high track (and photon) fluxes. RICH counters with CsI as the photo-sensitive substance will be used in HADES, COMPASS and ALICE experiments. A prototype of the ALICE RICH is being used in the STAR experiment at RHIC.

D. New photon detector: HPD for LHCb

In the framework of the LHCb experiment several photon detectors were considered as candidates for their system of RICH counters [31]. Two of them are based on a new technique which combines a vacuum photosensitive device with charge particle detection in a silicon detector with pixel readout. As a shown in Fig. 11, photoelectrons are accelerated by an electric field over a potential difference of about 20 kV towards a silicon detector with integrated electronics, and result in a signal of ≈ 5000e. The baseline solution is being developed in collaboration with the DEP company [34]. Presently the 1024 channel silicon detector is under development, so that in the beam tests (Fig. 12) a version of the same device with 61 pixels was used.

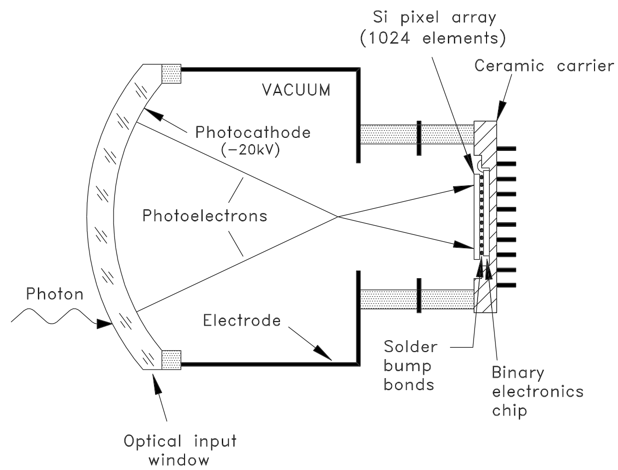
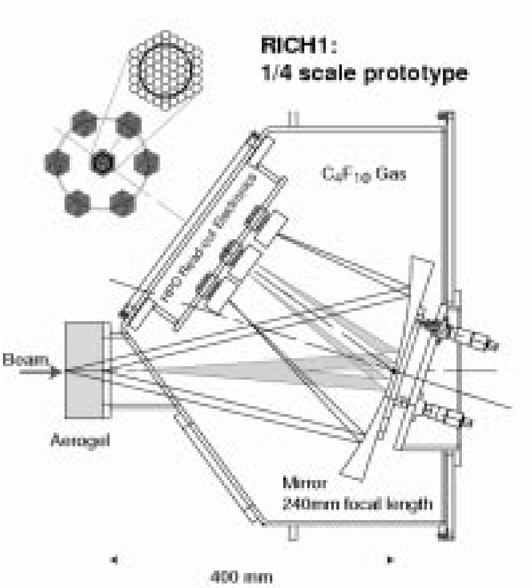


Fig. 11. Hybrid photon detector (HPD) of the LHCb experiment [31]. The outer diameter of the detector is 17 cm.

III. Light concentrators: systems of lenses

A common drawback of presently available vacuum based photon detectors is a rather large fraction of dead area. Recently new solutions were found which overcome



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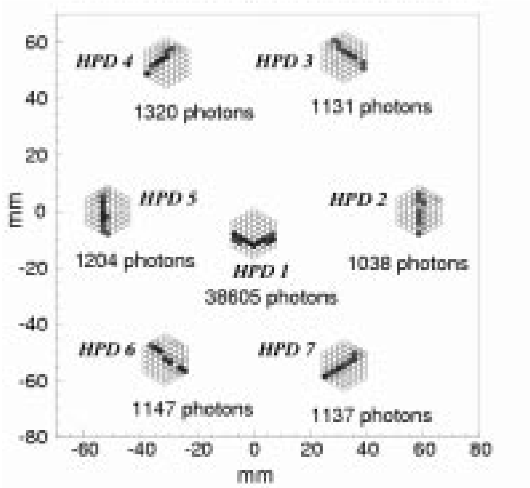

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Fig. 12. HPD beam test with two radiators, gas and aerogel [31]: (a) set-up and (b) hit distribution on the photon detectors.

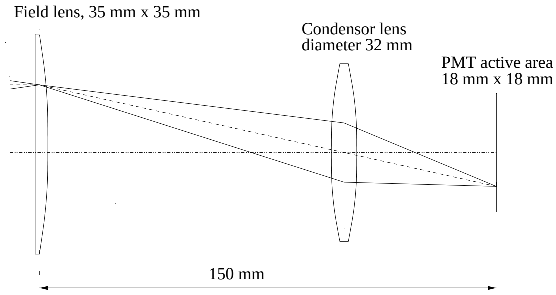


Fig. 13. Light collection in the HERA-B RICH: a system of two UVT acrylic lenses [33].

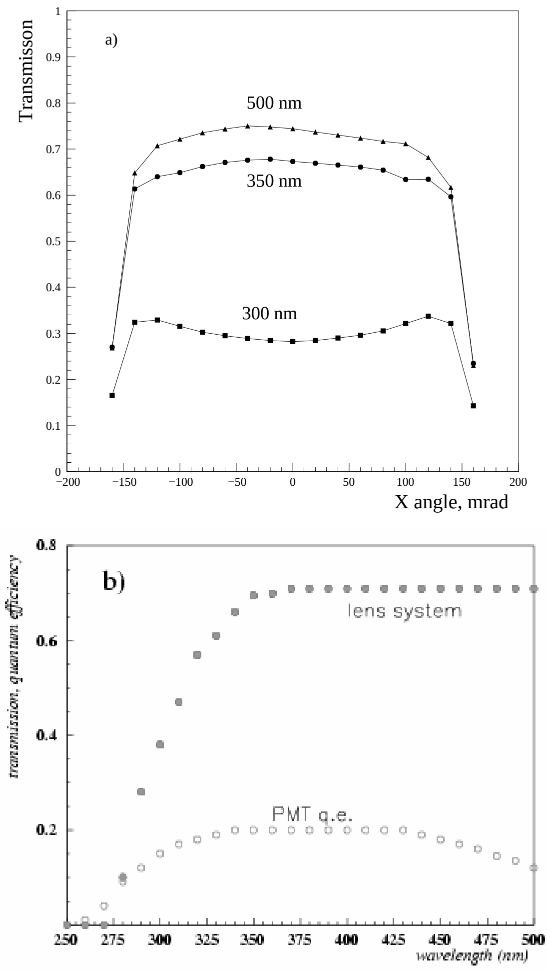


Fig. 14. HERA-B lens system: angular acceptance for three different wavelengths (a), transmission as a function of wavelength compared to the quantum efficiency of the PMT (b) [33].

this problem. In the HERA-B RICH a system of two lenses (Fig. 13) is used to demagnify the image on the focal surface by a factor of 2.1 [33]. The system of lenses is in this case used both to diminish the dead area, as well as to adapt the required granularity of the photon detector to the granularity of the multianode PMT. As shown in Fig. 14, the transparency of the system matches the quantum efficiency of the tube. It also has a flat acceptance for photons with incidence angles below 120 mrad, as required in the design specifications.

Lenses are also used in connection with the multianode PMT version of the LHCb RICH photon detector [31]. In this case, however, a single lens made of quartz is used as shown in Fig. 15.

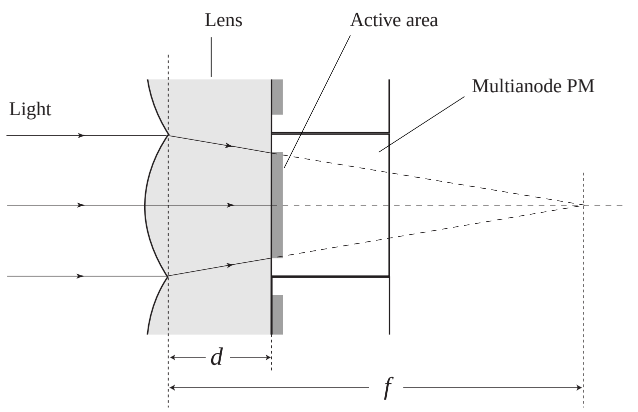


Fig. 15. Light concentrator for one of the LHCb photon detector options, a single quartz lens with a multianode PMT [31].

IV. Radiators

A. Aerogel for the Belle threshold counters

Aerogel materials with refractive indices between 1.01 and 1.10 fill the gap between gases ($n < 1.0015$), and liquids and solids ($n > 1.26$). Until a few years ago, aerogel materials had large pores, which caused considerable Rayleigh scattering even in the visible light region. With new production methods [35], [36] the scattering became acceptably low. In addition, aerogel material was found which is hydrophobic.

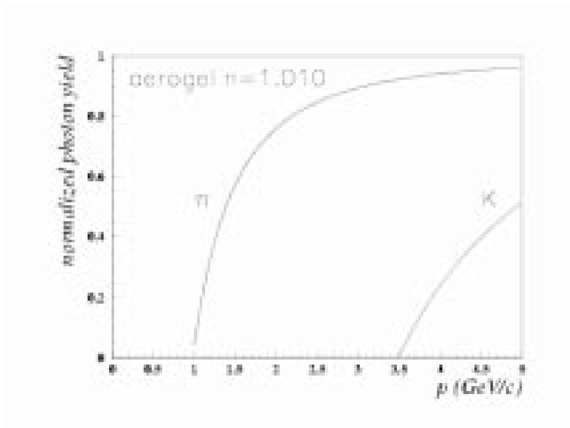
In the Belle spectrometer the separation of kaons from pions (an example of which is shown in Fig. 16) is performed by properly choosing n for a given kinematic region, such that kaons are below and pions above threshold [38].

B. Aerogel for RICH counters

The improved transmission of aerogel materials has also made possible the use of them as radiators for ring imaging counters [37]. The HERMES experiment [39] was the first to successfully employ aerogel in a RICH counter (Fig. 17). Beam tests for the LHCb RICH counters (Fig. 12) also gave satisfactory results [31].

V. New technique: DIRC

A novel type of ring-imaging Čerenkov counters is employed in the BaBar spectrometer. The DIRC counter is based on the Detection of Internally Reflected Cherenkov light. The principle is shown in Fig. 18. The patterns on the photon detector are quite complicated, but result in well resolved peaks in the Čerenkov angle distribution. The performance parameters (Fig. 19) of the counter were determined from the recorded data [32]. The number of photons per saturated ring depends on the angle of incidence of the charged track, and always stays above 20. The identification efficiency was determined by using charged tracks from the decay sequence $D^{*+} \to \pi^+ D^0 \to \pi^+ K^- \pi^+$. The efficiency for kaon identification exceeds 90% in the momentum range 0.5 GeV/c - 3 GeV/c, while the probability



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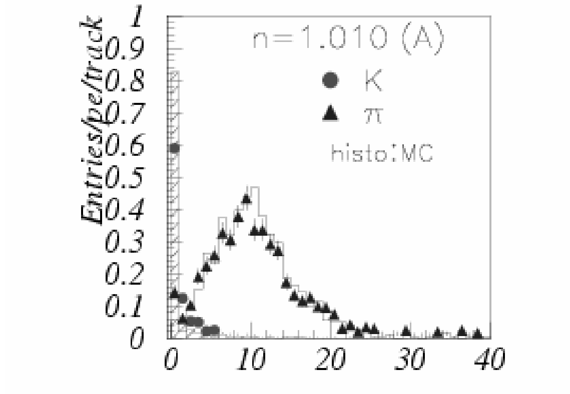

(b)

Fig. 16. Separation of K and π in the Belle spectrometer, in the momentum interval between 2 and 3.5 GeV: (a) expected yield for pions and kaons normalised to the maximal value, and (b) the measured distribution of the number of detected Čerenkov photons [38].

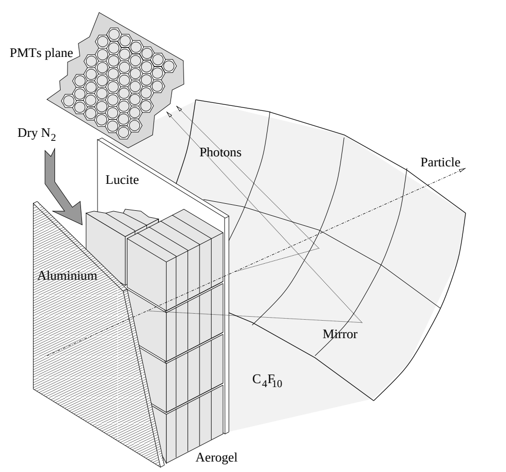

Fig. 17. The HERMES RICH counter with aerogel and gaseous radiators [39].

that a pion is identified as a kaon stays at a few percent level.

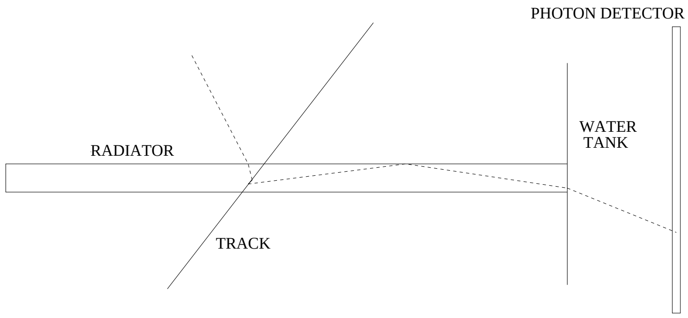

Fig. 18. Principle of the DIRC counter. Quartz is used as the radiator, and PMTs as photon detector.

VI. RICH counters with several radiators

The kinematic region covered by a RICH counter, from p_{min} to p_{max} , depends on the threshold momentum for the lighter of the two particles we want to separate, $p_t = \beta_t \gamma_t mc$, $\beta_t = 1/n$, and typically $p_{min} = \sqrt{2} p_t$. The upper limit in momentum p_{max} is set by the the resolution in Čerenkov angle (ultimately given by the dispersion in the radiator medium). It turns out that for most radiators [6]

$$\frac{p_{max}}{p_{min}} \approx 4 - 7. \tag{4}$$

This, in turn, tells us that for a larger kinematic interval we need two or more radiators. While in SLD and DELPHI a combination of the liquid C_6F_{14} and gaseous C_5F_{12} (or C_4F_{10}) was used, the HERMES (Fig. 17) and LHCb (Fig. 20) RICH counters combine aerogel with gaseous radiators. LHCb has gone even further: to cover a kinematic region with $p_{max}/p_{min} \approx 200$, they employ three radiators in two counters [31].

VII. RICH at high track densities

The accumulated experience of the HERA-B collaboration shows that a RICH counter can safely be operated even at high track densities [18]. A typical event is in this case shown in Fig. 21 (in contrast to Fig. 4). Typical rates are above 1 MHz per channel in the hottest part of the detector. The counter has been in operation since summer 1998, and no degradation of performance has been observed. The relevant RICH parameters were determined from the data. The figure of merit is $N_0 = 43$ cm^{-1}, resulting in 32 photons per saturated ring. The single photon resolution is 0.7 mrad in the finer granularity area covered by R5900-M16 tubes, and 1.0 mrad with R5900-M4 PMTs. All parameters are in very good agreement with expectations. Preliminary results of particle identification as shown in Fig. 22 are promising. It is expected that they improve while the tracking system is getting better aligned.

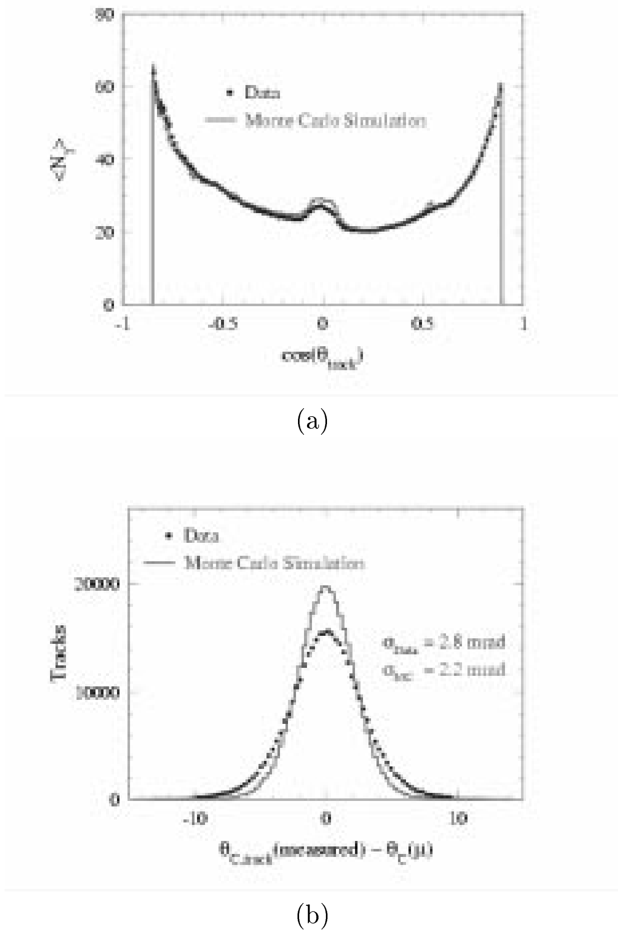

Fig. 19. DIRC performance: (a) average number (N_γ) of detected photons per track, (b) deviation of the measured Čerenkov angle from the nominal value [32].

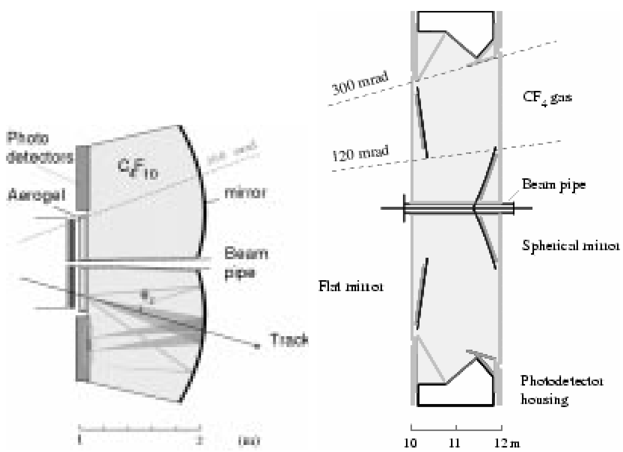

Fig. 20. RICH counters for LHCb [31].

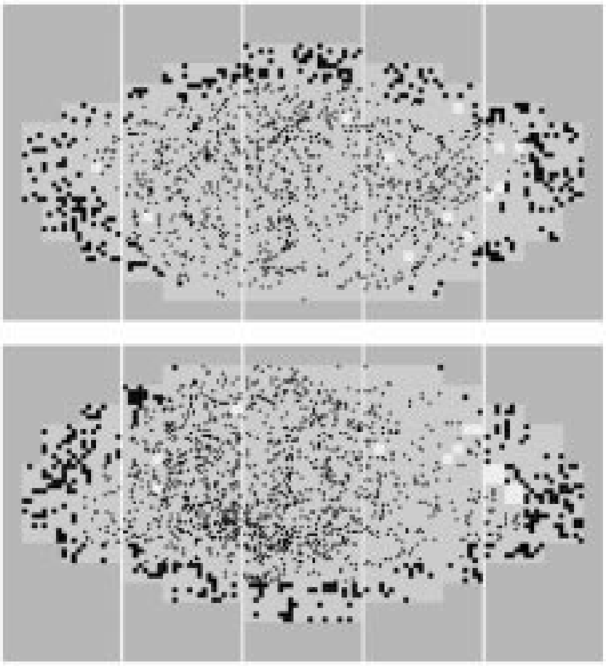

Fig. 21. Typical event as recorded with the RICH counter (Fig. 2) of the HERA-B experiment.

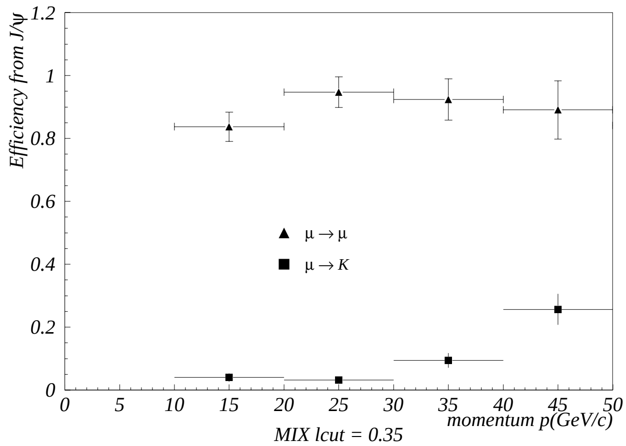

Fig. 22. Particle identification in the HERA-B RICH: efficiency to identify a muon, as deduced from the $J/\psi \to \mu\mu$ decays.

VIII. Summary

Čerenkov counters have gone a long way in the last decade. They have become a standard tool in particle physics, and have overcome the problematic childhood era. The next generation of counters for experiments at hadron colliders is getting ready.

It is worth noting that the knowledge accumulated in the research and development of Čerenkov counters has found use in other areas. In environmental physics, it is used in monitoring of pure β emitters (^{90}Sr) through their detection via Čerenkov light emitted in aerogel [40]. In medical applications the experience with photon detectors can be used for development of scintillation light detectors in medical imaging, e.g. CsI and TMAE with BaF_2 for positron emission tomography (PET), multianode PMTs with GSO for positron emission mammography (PEM) [41]. An example of technology spin-off of these techniques can be found in [42]. Finally, pattern analysis in RICH counters is often closely related to algorithms in medical imaging (e.g. expectation-maximisation algorithm for PET, Hough transform).

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