Detectors for particle identification

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Abstract

The paper reviews recent progress in particle identification methods. A survey of motivations and requirements for particle identification in various experimental environments is followed by the main emphasis, which is on the recent development of Cherenkov counters, from upgrades of existing devices to a novel focusing radiator concept and new photon detectors. The impact of including a precise measurement of the time of arrival of Cherenkov photons to increase the kinematical region over which particle identification can be performed is discussed. The progress in dedicated time-of-flight counters with recently developed very fast single photon detectors is also evaluated.

1. Introduction

One of the main driving forces of the research and development of particle identification methods in the last decade was the need to have excellent hadron identification for precision *B* physics measurements. For a statistically significant measurement of CP violation in the *B* system, the tagging of *B* meson flavour with the kaon charge was an indispensable method. In addition, for the study of rare few body hadronic decays of *B* mesons it is essential to separate pions from kaons up to the kinematic limits of the experiment. Reliable hadron identification is also important in the search for quark-gluon plasma and in studies of the nucleon structure.

Hadrons are identified by their mass, which is, in turn, determined by combining the measurements of momentum and velocity. Assuming that momentum is inferred from the measured radius of curvature in magnetic field, the remaining issue is to measure the velocity with a sufficient precision. This is either achieved by measuring the time-of-

flight (TOF), ionization losses or Cherenkov angle of the particle. In the present contribution recent progress in Cherenkov counters and TOF measurements is discussed.

The structure of the paper is as follows. We first review the Cherenkov counters in some of the running or recently completed experiments. A number of new methods is presented, from upgrades of existing devices to a novel focusing radiator concept and new photon detectors. We then discuss the benefits of including a precise measurement of the time of arrival of Cherenkov photons in order to reduce the dispersion error and the even more ambitious use in a combined TOF and time-of-propagation (TOP) counter. Finally, we will discuss the progress in dedicated TOF counters with recently developed very fast photon detectors.

2. Cherenkov counters

2.1. DIRC at BaBar

The DIRC (Detector of Internally Reflected Cherenkov light) of the BaBar spectrometer is a special type of a ring-imaging Cherenkov counter [1], based on the detection of Cherenkov photons trapped in the quartz radiator bar

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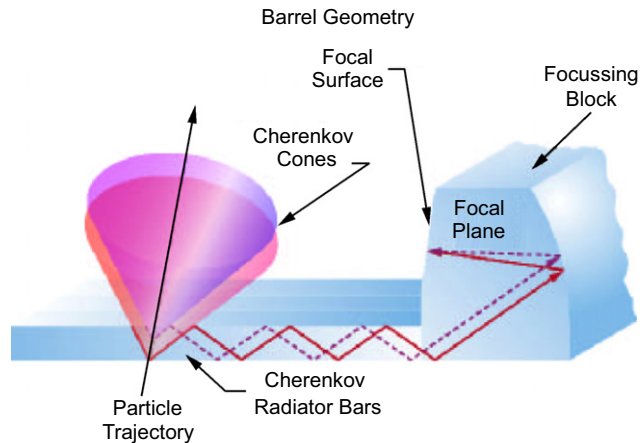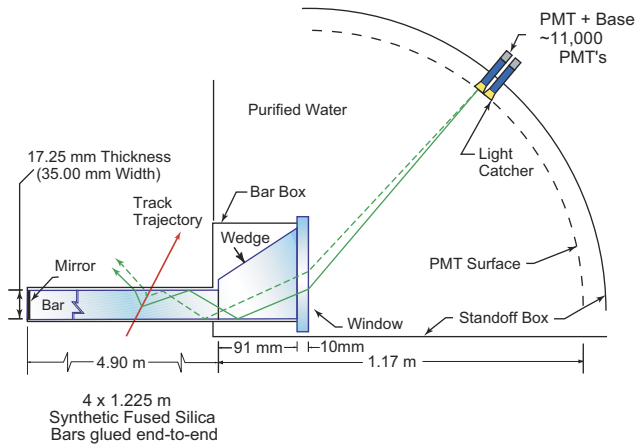E-mail address: peter.krizan@ijs.si

Fig. 1. Principle of the DIRC counter (top) and its upgrade, the focusing DIRC (bottom).

Fig. 2. Particle identification with DIRC: K efficiency and $\pi \to K$ missidentification probability.

(Fig. 1). The patterns on the photon detector are quite complicated, but result in well resolved peaks in the Cherenkov angle distribution. The time of arrival of photons is used to eliminate background from conversion events in the water tank, to assign photons to proper tracks, and to eliminate most of the ambiguities in the photon-track reconstruction.

The basic performance parameters of the counter are in excellent agreement with expectations [1]. The single photon resolution amounts to 9.6 mrad. The number of photons depends on the polar angle of the charged track, but always stays above 20 for $\beta = 1$ particles. The efficiency for kaon identification exceeds 90% in the momentum range $0.5-3\,\text{GeV}/c$, while the probability that a pion is identified as a kaon stays at a few percent level (Fig. 2).

2.2. ACC at Belle

In the Belle spectrometer the separation of kaons from pions is performed with the Aerogel Cherenkov Counter (ACC), a threshold Cherenkov detector (Fig. 3) with aerogel as radiator [2]. The refractive index of the radiator
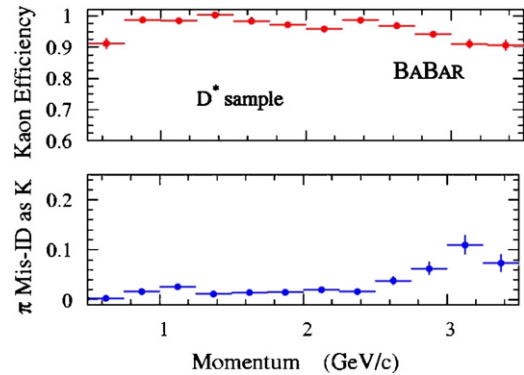
is chosen so that pions emit Cherenkov light, while kaons stay below threshold. Since the momentum spectrum of particles becomes harder in the forward direction, the refractive index of the modules gradually decreases from $n = 1.028$ to $n = 1.01$. Note that while in the central (barrel) part it is possible to measure both the tagging kaons and the $B \to \pi\pi, K\pi$ decay products, only the former can be identified in the forward (endcap) direction. The kaon identification efficiency amounts to 90% with the pion fake probability equal to 6% [3].

2.3. HERA-B RICH

The HERA-B collaboration was the first to employ multianode photomultiplier tubes in a RICH counter (Fig. 4) [4], after having shown that the Hamamatsu R5900 PMTs (versions M16 and M4 with 16 and 4 square shaped channels, respectively) have a capability to detect single photons with high efficiency and little cross-talk [5]. The photon detector performed very well, showing clear rings with very few noisy channels ($<0.5\%$) even in a very hostile environment of a hadron machine, as can be seen from Fig. 5.

A common drawback of vacuum based photon detectors is a rather large fraction of dead area. While for single channel PMTs reflective cones can be used, multichannel PMTs need an imaging system. In the HERA-B RICH a system of two lenses, shown in Fig. 6, was used to demagnify the image on the focal surface by a factor of 2 [6]. The system of lenses is used both to reduce the dead area, as well as to adapt the required granularity of the photon detector to the granularity of the multianode PMT. The transparency of the system is high in the region of high quantum efficiency of the tube. It also has a flat acceptance for photons with incidence angles below 140 mrad as required by the detector geometry.

The experience of the HERA-B collaboration shows that a RICH counter can safely be operated even at high track densities with counting rates exceeding 1 MHz per channel in the hottest part of the photon detector [4]. A typical
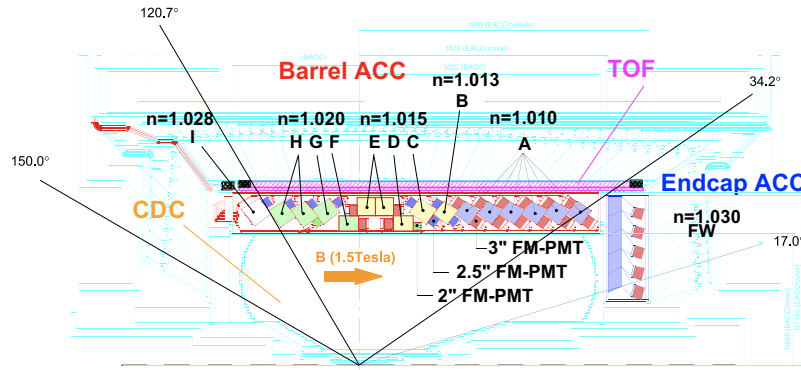
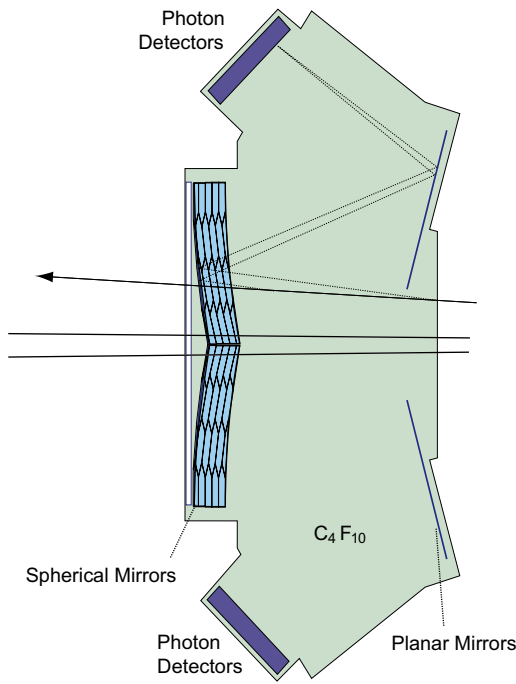Fig. 3. Aerogel Cherenkov Counter (ACC) of the Belle spectrometer.

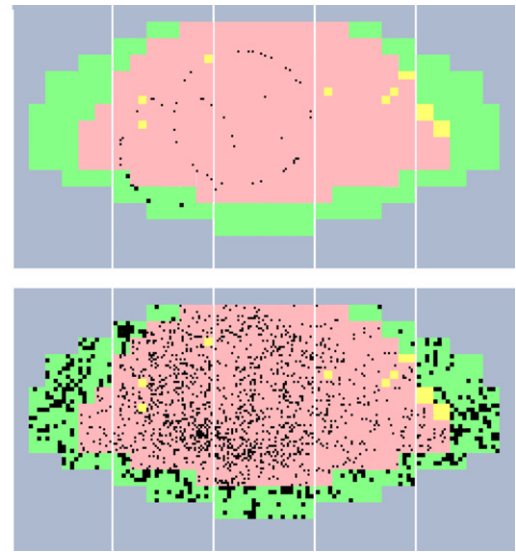Fig. 4. Layout of the HERA-B RICH counter.

Fig. 5. Events recorded in the lower half of the HERA-B RICH: a low multiplicity event (top) with two clear rings, and a typical event (bottom).

event is shown in the lower plot of Fig. 5. No degradation of performance has been observed over the five years of operation. The relevant RICH parameters were determined from the data. On average 32 photons were detected per $\beta = 1$ ring. The single photon resolution was 0.7 mrad in the finer granularity area covered by R5900-M16 PMTs. All parameters are in very good agreement with expectations. The particle identification capabilities are illustrated in Fig. 7.

2.4. COMPASS, Hades and ALICE RICH counters

The RICH counters of COMPASS [7], Hades [8] and ALICE [9] experiments employ multiwire chambers with a solid CsI layer, evaporated onto the cathode pads, as the photon detector. The material requires a high purity chamber gas, usually methane with water and oxygen content of the order of ppm, as well as careful handling of the photo-cathodes. A lot of R&D (influence of substrate, thermal conditioning, thickness, evaporation procedure, transfer to the chamber) was needed to make the technique mature [10,11]. A special evaporation plant with a sophisticated conditioning facilities and quality assessment controls was constructed at CERN for this purpose. While Compass and Hades RICH counters have been running stably for several years, the ALICE RICH is under construction [12].

In the Compass experiment the central region of the RICH counter was recently upgraded to enable running at higher beam intensities, higher trigger rates and with a nanosecond time resolution for background suppression [13]. The wire chamber based photon detector was replaced by an array of multianode PMTs very similar to the HERA-B RICH (Section 2.3). The PMTs, again Hamamatsu 16 channel tubes, have quartz windows, and the 7:1
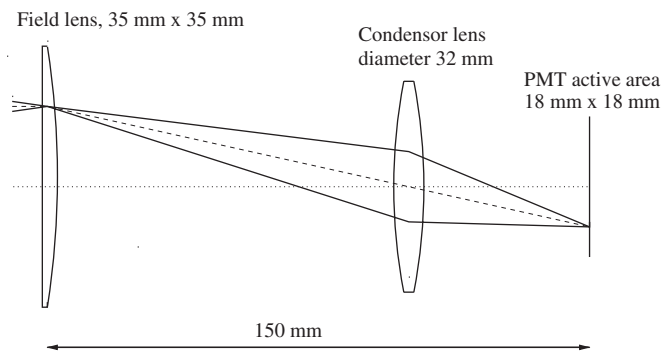
Fig. 6. The optical system for light collection and demagnification of the HERA-B RICH. The two rays shown in full line correspond to photons with incident angles of ± 100 mrad with respect to the normal incidence (dashed line).
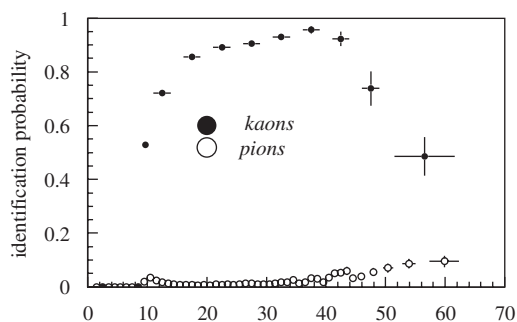

Fig. 7. Particle identification in the HERA-B RICH: efficiencies to identify a kaon and misidentify a pion, as deduced from the $\phi \to K^- K^+$ and $K_S \to \pi^- \pi^+$ decays.

demagnification two-lens light collection system is made of quartz lenses. This results in a larger number of detected photons (≈ 60 per ring for $\beta = 1$ particles). The measured Cherenkov angle resolution per track is ≈ 0.3 mrad, allowing a 2σ π/K separation at $60 \,\text{GeV}/c$. The kaon identification efficiency exceeds 90% with $\pi - K$ misidentification probability at $\approx 1\%$.

2.5. LHCb RICH

In the next generation of B physics experiments at hadron colliders the identification of hadrons will again be essential for both the tagging of b-flavour in CP violation and for mixing measurements, as well as for the identification of particles in hadronic final states such as $B \to \pi^+ \pi^-$. In particular, this is so because more channels contribute to the background than in the case of experiments at $\Upsilon(4s)$ (e.g. $B_s \to K^+ K^-$). In the LHCb experiment the RICH counter is designed to cover π/K separation between 1 and $150 \,\text{GeV}/c$ [14]. 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 one wants to separate, and on the resolution in Cherenkov angle (ultimately given by the dispersion in the radiator medium). It turns out that for most radiators $p_{\max}/p_{\min} \approx 4-7$ [15]. For the large kinematic interval in the LHCb

experiment one would therefore require three radiators. They are arranged in two counters [14] as shown in Fig. 8.

Several photon detectors were considered as candidates for the system of RICH counters; a photon detector based on multianode PMTs with a single quartz lens light collection system [16], as well as two types of hybrid photon detectors (HPD). In the latter, a vacuum photo-sensitive device is combined with charged particle detection in a silicon detector with pixel readout [17]. As shown in Fig. 9, photoelectrons are accelerated by the electric field across a potential difference of about $20 \,\text{kV}$ towards a silicon detector with integrated electronics. The results of beam tests of the final module, developed in collaboration with the DEP company, are very encouraging [18].

3. Recent developments in RICH counters

For the next round of B physics experiments at upgraded $e^+ e^-$ machines ("Super B factories") with luminosities exceeding $10^{35} \,\text{cm}^{-2} \,\text{s}^{-1}$, considerable improvements of particle identification devices are envisaged in order to cope with higher rates and with more stringent requirements on separation capabilities for rare decay channels.

3.1. Upgrades at Belle

Two systems are being considered for the upgrade of the Belle spectrometer [19]. For the barrel region a TOP counter is being studied. This is a kind of DIRC counter in which the Cherenkov angle is deduced by measuring one of the coordinates and the time of arrival of Cherenkov photons with high precision [20]. Multianode micro-channel plate (MCP) PMTs, including a detector with a GaAsP photocathode, are being investigated [21].

For the endcap region, a proximity focusing RICH with aerogel as radiator is being tested (Fig. 10). The counter should have a low threshold for pions, and should enable good separation of pions and kaons up to $4 \,\text{GeV}/c$. Another benefit of such a counter would also be a reasonable $e/\mu/\pi$ separation at low momenta, which is of importance for the studies of rare $B \to K\ell\ell$ decays.
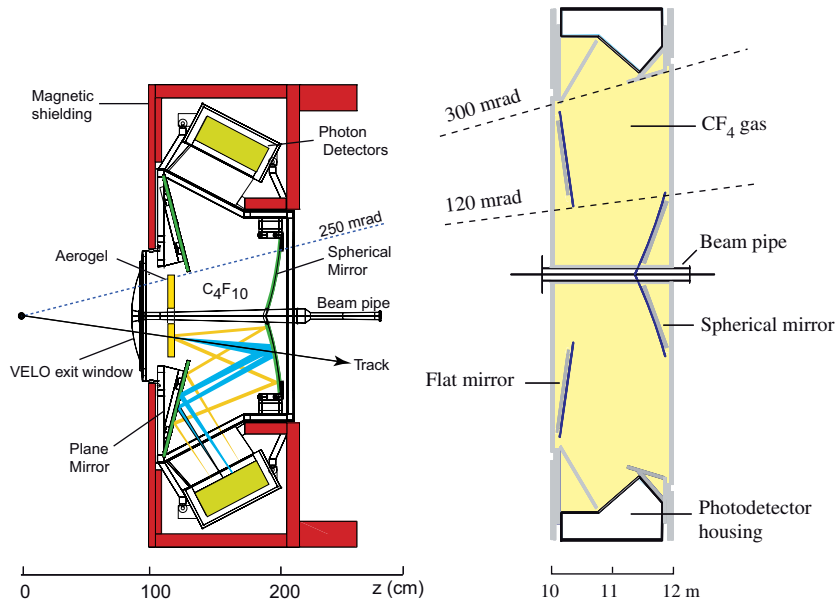
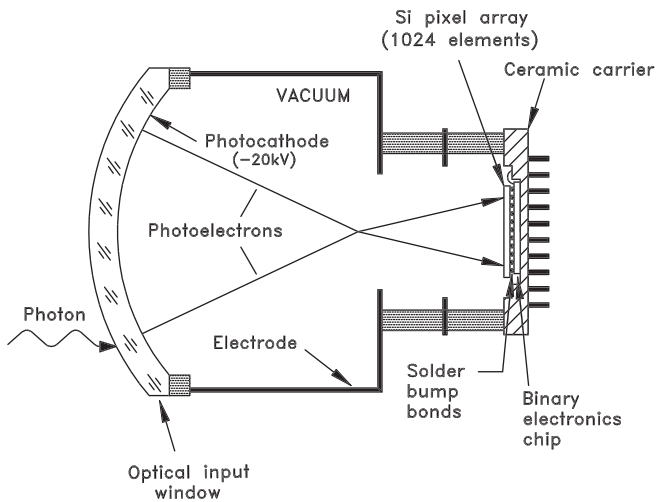Fig. 8. RICH counters for the LHCb experiment.

Fig. 9. Hybrid photon detector (HPD) of the LHCb experiment. The outer diameter of the detector is 17 cm.

The feasibility of such a counter was studied in a series of beam tests [22,23]. Hamamatsu H8500 (flat panel') PMTs were used as photon detectors [24]. As can be seen from Fig. 10, the Cherenkov peak is well pronounced above a small background, mainly coming from Cherenkov photons which were Rayleigh scattered in the radiator. The resolution in the Cherenkov angle measurement ($\sigma_\theta = 14$ mrad) and the number of detected photons ($N \approx 6$, Fig. 10) agree well with expectations. The resulting resolution per track is about 5.7 mrad. Since the difference in Cherenkov angle of pions and kaons is 22 mrad at $4\,\text{GeV}/c$, such a counter would allow a good (about 4σ) separation up to the kinematic limit of the experiment.

The key issue in the performance of a proximity focusing RICH counter is to improve the Cherenkov angle resolution per track $\sigma_{\text{track}} = \sigma_\theta/\sqrt{N}$. As it turns out, the

optimal thickness is expected to be around 20 mm [22,25]. However, this limitation can be overcome in a proximity focusing RICH with a non-homogeneous radiator [25–28]. By judiciously choosing the refractive indices of consecutive aerogel radiator layers, one may achieve overlapping of the corresponding Cherenkov rings on the photon detector (Fig. 11) [28]. This represents a sort of focusing of the photons within the radiator, and eliminates or at least considerably reduces the spread due to emission point uncertainty. Note that such a tuning of refractive indices for individual layers is only possible with aerogel, which may be produced with any desired refractive index in the range 1.01–1.07 [29]. The dual radiator combination can readily be extended to more than two aerogel radiators. In this case, the indices of aerogel layers should gradually increase from the upstream to the downstream layer.

In Fig. 12, we compare the data for two 4 cm thick radiators; one with aerogel tiles of equal refractive index ($n = 1.046$), the other with the focusing arrangement ($n_1 = 1.046, n_2 = 1.056$). The improvement is clearly visible. The single photon resolution $\sigma_\theta = 14.3$ mrad for the dual radiator is considerably smaller than the corresponding value for the single refractive index radiator ($\sigma_\theta = 20.7$ mrad), while the number of detected photons is the same in both cases.

The present R&D efforts are oriented mainly toward the development of a photon detector which works in the high magnetic field (1.5 T) of the Belle spectrometer. The Burle 85011 MCP PMT [30], a multichannel device with 8×8 channels and $6\,\text{mm} \times 6\,\text{mm}$ large pads, has been shown to perform very well as a detector of Cherenkov photons in a RICH counter [31].

Two further detectors are being studied. In a joint effort with the Hamamatsu company a new type of hybrid photon detector of the proximity focusing type is being
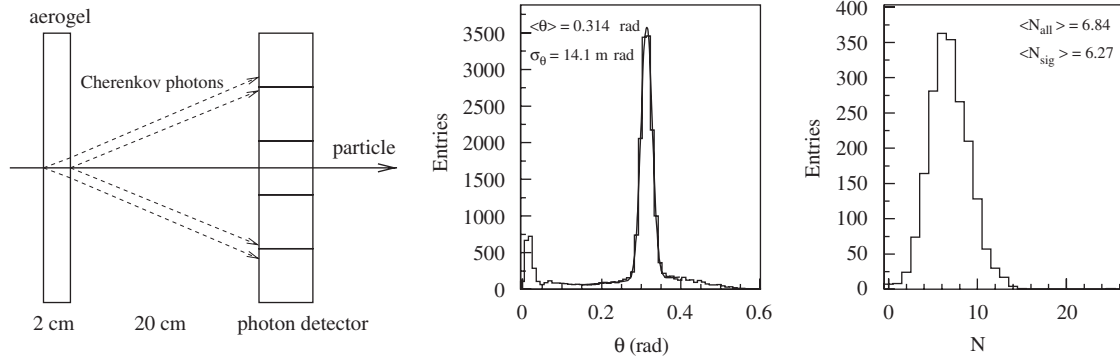
Fig. 10. Proximity focusing RICH for the Belle upgrade in the endcap region: schematic (a), measured single photon resolution (b) and the number of detected photons (c) for a 2 cm thick aerogel tile.
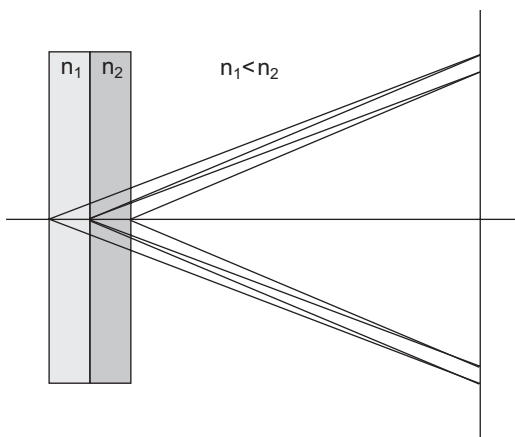

Fig. 11. Proximity focusing RICH with a nonhomogeneous aerogel radiator in the focusing configuration.

developed. As the second option, silicon photomultipliers, novel semiconductor photon detectors are being tested [32–34]. They have several advantages: insensitivity to the high magnetic fields, lower operation voltage, and less material in comparison to the conventional photomultiplier tubes. They also have high peak photon detection efficiency (approx 20%), high gain of $\approx 10^6$ and good time response. Due to their dimensions, they allow compact, light and robust mechanical designs. All this would make them a very promising candidate for a detector of Cherenkov photons in a RICH counter. However, due to the serious disadvantage of a very high dark rate ($\approx 10^6$ Hz/mm^2), they have up to now never been used in ring imaging Cherenkov detectors, where single photon detection is required at low noise. Because the Cherenkov light is prompt, this problem could in principle be reduced by using a narrow time window (<10 ns) for signal collection. In addition, it is possible to further increase the signal-to-noise ratio by using light collection systems [35].

3.2. Focusing DIRC

As an upgrade of the DIRC counter, a layout with a considerably smaller stand-off box is being considered [36] as shown in Fig. 1. Such a change would significantly reduce the beam related background. However, in order not to degrade the angular resolution, single channel PMTs would have to be replaced by multichannel devices among which the Hamamatsu flat panel 64 channel PMTs and the Burle 64 channel micro-channel plate (MCP) PMTs have been studied. Two further changes are considered which should considerably improve the angular resolution. The uncertainty in the emission point along the track will be eliminated by focusing optics of the expansion volume made of quartz. The chromatic error will be reduced by measuring the time of arrival of Cherenkov photons with a resolution of 50–100 ps, from which the wavelength of each photon can be estimated. The expected resulting total angular error is 4–5 mrad per single photon, which makes it possible to achieve an angular resolution of 1.5 mrad per track in principle. While the present BaBar DIRC achieves a 2.7σ π/K separation at 4 GeV/c, the equivalent performance of the upgraded DIRC would be 4.3σ at 4 GeV/c for photons traveling a full bar length of 3–4 m.

To demonstrate the capability of eliminating the chromatic error contribution, tests of candidate photon detectors were carried out to evaluate their timing resolution and homogeneity of response [37]. By using a pulsed laser diode and dedicated read-out electronics, the time resolution of the MCP PMTs was measured. An excellent time resolution of 30 ps was achieved [38,39]. The performance of a focusing DIRC prototype was successfully tested in a test beam [39].

4. Recent progress in time-of-flight counters

A proximity focusing RICH counter such as the one discussed in Section 3.1 is also a very fast counter, in particular, if a micro-channel plate (MCP) PMT is used as the photon detector. With its excellent timing properties, the same device could also serve as a time-of-flight counter and thus supplement other identification methods, in particular for low momentum tracks. Cherenkov photons emitted in the radiator medium as well as in the entrance window of the PMT can be used for the TOF measurement
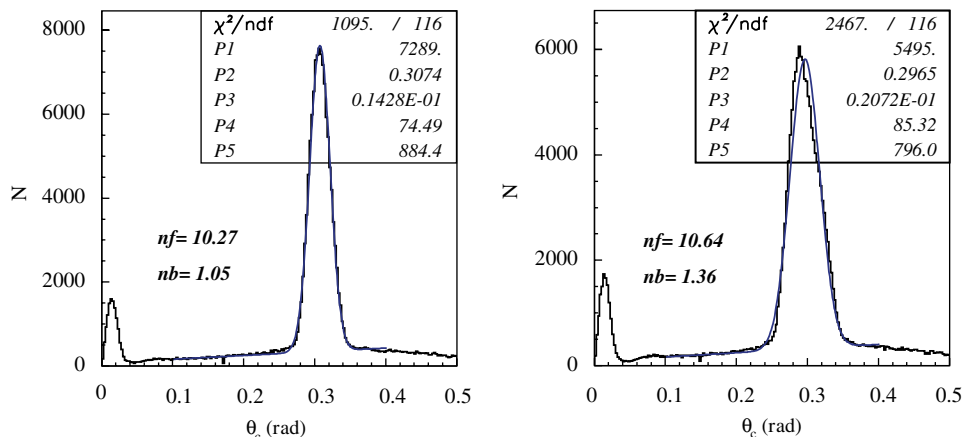
Fig. 12. The accumulated distribution of Cherenkov photon hits depending on the corresponding Cherenkov angle for a 4 cm homogeneous radiator (right) and a focusing configuration with $n_1 = 1.046$, $n_2 = 1.056$ (left).
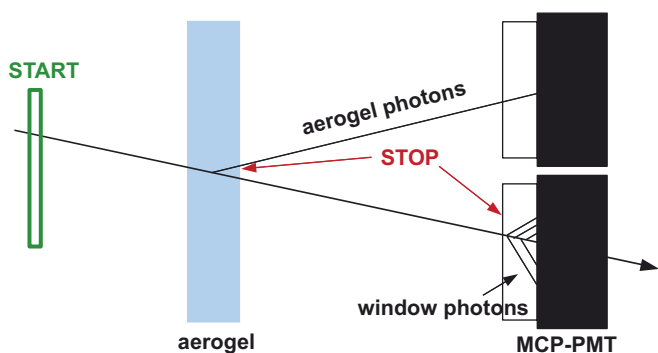

Fig. 13. Schematic view of a combined RICH and TOF counter.

(Fig. 13). This allows a positive identification also of particles that would be below the Cherenkov threshold in the aerogel radiator (kaons and protons in the region around 1 GeV). Consequently, a good separation of kaons and protons would be possible in this region as well.

To test this idea, in a beam test both the hit position and its time were registered with a Burle 85011 MCP PMT [40]. The distributions of hits, depending on their time of flight for Cherenkov photons from the aerogel, is plotted in Fig. 14. Fitting this distribution with a Gaussian function yields a standard deviation of about 50 ps. For 10 detected hits per track this would correspond to a TOF resolution of 20 ps.

An excellent resolution is also found in the TOF distribution as determined by Cherenkov photons from the PMT window. As can be seen in Fig. 14, the standard deviation of the distribution for pions is 37 ps. We can also see that pions are clearly separated from protons even in this very compact set-up with a very short flight path of 65 cm. In the Belle spectrometer, where the typical flight path is about 2 m, the measured performance would correspond to a 6 σ separation between pions and kaons

at 2 GeV/c, and a 3.5 σ separation between protons and kaons at 4 GeV/c.

To further improve the time resolution, one could increase the number of photons to about 50 by adding an additional 1 cm thick quartz radiator in front of the PMT. This idea was tested in a set-up with a somewhat faster version (Burle 85001-501 P01) of the same MCP PMT with 10 μm pores (instead of 25 μm), and with a pulsed laser as a source of photons [39]. In Fig. 15 the improvement in resolution is clearly observed. By using an even thicker radiator (up to 5 cm), a time resolution of 6 ps was observed [41]. With such a resolution the TOF counter becomes quite competitive with a RICH counter in the kinematical region up to 4 GeV/c.

5. Summary

Particle identification devices, in particular, the Cherenkov counters of the BaBar and Belle spectrometers have contributed significantly to the rich *B* physics harvest of the last seven years. Identification of particles in the final state with Cherenkov counters has also contributed to the present understanding of nucleon structure and of the production of heavy quarks in nucleon–nucleon collisions. Upgrades are planned to further improve their performance and to allow them to work at even higher event and background rates. New techniques, including a novel focusing radiator concept and new fast photon detectors, have been successfully studied. By using the time of arrival of Cherenkov photons, the dispersion error could be reduced. Furthermore, a RICH counter equipped with fast photon detectors can be combined with a time-of-flight or a time-of-propagation counter. Finally, a new type of TOF counter was studied with the same very fast photon detectors. It is expected that these particle identification methods will again play a decisive role in the next generation of precision experiments in *B* physics.
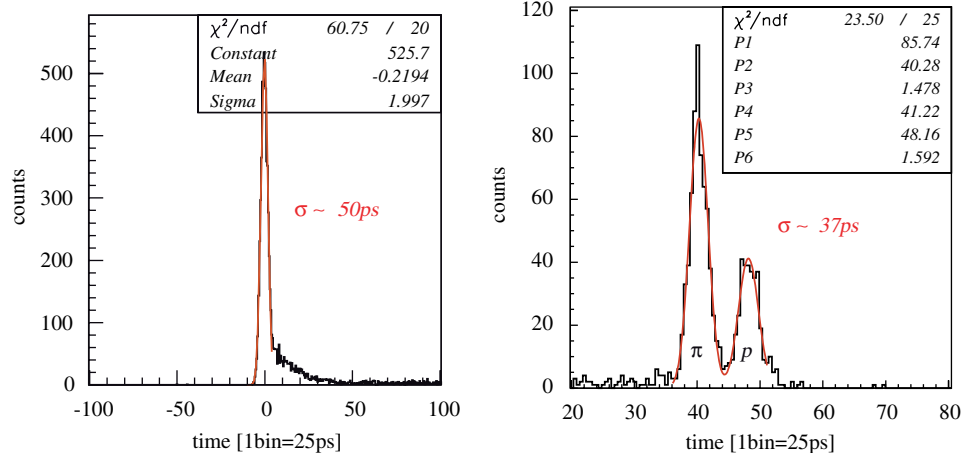
Fig. 14. The distribution of the time of flight as measured by single Cherenkov photons from the aerogel radiator (left), and by Cherenkov photons from the PMT window, shown for $2\,\mathrm{GeV}/c$ pions and protons (right).
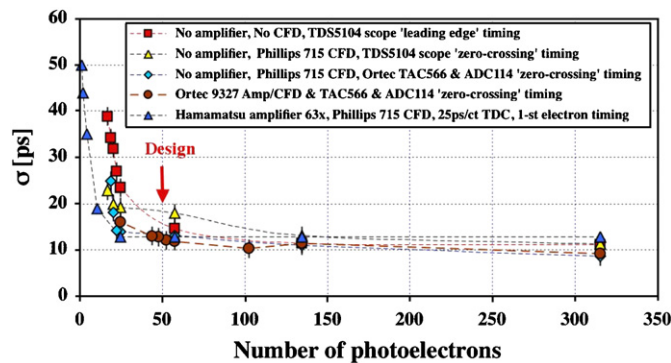

Fig. 15. Timing resolution as a function of number of photoelectrons using various methods for an MCP-PMT with $10\,\mu m$ hole diameter [39].

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