Focussing DIRC – A new compact Cherenkov ring imaging device

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Abstract

We present a new device for particle identification, the Focussing DIRC that fits into a tight detector configuration and fully exploits the potentiality of Cherenkov ring imaging technique in the momentum range of high-energy fixed-target and collider experiments. In the device, internally reflected Cherenkov rings in a thin quartz radiator plate are focussed by a toroidal mirror surface to arc-like loci at the circumference of the plate. The image is taken on the focal surface by segmented photon detectors or by tightly packed optical fibers of diameter around 1 mm. The focussing optics is implemented as extension of the radiator plate and occupies not more than about 10 cm by 12 cm in cross section. The image width of the Cherenkov ring is mostly determined by the chromatic dependence of the Cherenkov angle and the multiple Coulomb scattering in the radiator plate. We expect to separate pions and kaons by $\pm 3.5 - 4\sigma$ up to 3.5 GeV/c and by $\pm 3\sigma$ up at 4 GeV/c with presently available photon sensors. With higher quantum efficiency sensors such as VLPCs, we will be able to separate kaons from pions up to $\pm 10$ GeV/c with a 2 cm thick quartz radiator.

1. Introduction

Designing a particle identification device for an asymmetric $e^+e^-$ B-factory detector presents a challenge because measurements of CP violation require clear $\pi-K$ separation in the momentum region of $0.2 < p < 4.0$ GeV/c, both to reconstruct exclusive final states of $B$ meson decays and to tag the flavor ($b$ vs $\bar{b}$) of $B$ mesons, within geometrical constraints imposed by the surrounding electromagnetic calorimeter [1,2]. The challenge is far more difficult to meet in hadron collider $B$-experiments [3,4]: to tag $B$ and $\bar{B}$ decays, one needs a device that can identify $K$ from $\pi$ up to $\pm 10$ GeV/c or higher in a dense particle population and in a harsh radiation environment. Situation will be similar in future linear $e^+e^-$ collider experiments if $\pi/K$ separation is needed.

A Cherenkov ring imaging device based on the Detection of Internally Reflected Cherenkov light (DIRC) has been proposed by Ratcliff and collaborators [5,6] as a particle identification device for the BaBar experiment at the SLAC B-factory. A similar device [7] was also proposed to the BELLE experiment at the KEK B-factory. In these devices ("non-focussing DIRC") Cherenkov photons produced in a long quartz bar with a rectangular cross section are trapped by total internal reflection and transported to the ends of the bar, where they are proximity focussed onto an array of photomultiplier tubes through a large water-filled standoff. Here we present a new type of DIRC ("focussing DIRC") that does not require the large standoff and can easily fit into most high energy fixed-target and collider experiments [8–10]. In the focussing DIRC the Cherenkov radiator is a continuous (planar or curved) plate whose periphery forms a toroidal mirror surface by which the transported Cherenkov photons are focussed to an arc-like image. The image is captured either by tightly packed arrays of optical fibers or photon sensor arrays placed near the radiator plate. The fibers, if used, transport the image to photon sensor arrays.

In the present study, basic features of the focussing DIRC have been examined through beam tests of a prototype device [11] and its potentials have been explored by Monte Carlo simulations. A sample design with readout fibers and phototubes will be able to separate kaons from pions up to 3.5 GeV/c. Designs with photon sensors with high quantum efficiencies such as VLPCs [12] will allow us to separate kaons from pions up to about 10 GeV/c and muons from pions up to about 800 MeV/c.

2. Principle of focussing DIRC

A charged particle with velocity $\beta$ passing through the Cherenkov radiator with an index of refraction $n$ produces photons on a cone around the particle trajectory with a
half-angle $\theta_c = \arccos(1/n\beta)$ as depicted in Fig. 1. The angle ($\theta_c > 0$) individual photon makes to the radiator plane generally depends on the azimuth ($\phi_c$) on the Cherenkov cone, and the dip angle of the particle ($\theta_{\text{dip}}$). If $\theta_c$ is smaller than the critical angle of the internal reflection ($\theta_i = \arccos(n_i/n)$, where $n_i$ is the index of refraction for a material surrounding the radiator plate), Cherenkov photons will be trapped in the radiator (see Fig. 2). Because $\theta_c$ remains unchanged, the trapped portion of the Cherenkov cone is transported undistorted, except for the up–down ambiguity, to the periphery of the plate. We note here that the index of refraction ($n$) of quartz depends strongly on the photon’s wavelength in the UV band and so does $\theta_c$.

Fig. 3 shows the distribution of $\theta_c$ for photons produced by a particle with $\beta = 1$ in a quartz plate ($n = 1.48$, $\theta_c = 47.5^\circ$ at $\lambda = 320$ nm) as a function of $\phi_c$ and $\theta_{\text{dip}}$. Here, $\phi_c = 0$ is taken as the direction of the particle projected on the radiator plate.

The radiator designed for the end-cap of collider experiments (e.g. the BELLE experiment at KEK) is shown in Fig. 4 as the Sample Design No. 1 [9,10]. It is a 2 cm thick synthetic quartz disk extending from 0.5 to 1.2 m in radius. High energy particles coming from the colliding point produce Cherenkov cones which are tilted outwardly.

![Fig. 1. Definition of angles used in the present work.](image1)

![Fig. 2. Schematic drawing to illustrate the transport and focussing of Cherenkov photons in the device. Photons with the same $\theta_c$ and $\phi_c$ are focussed on the same position on the focal plane, regardless of their emission point along the particle trajectory. The $x$ coordinate is related to $\phi_c$ but not linearly correlated.](image2)

![Fig. 3. Distribution of the angle $\theta_c$ that Cherenkov photons make to the radiator plate as a function of the azimuth angle $\phi_c$ on the Cherenkov cone and the dip angle $\theta_{\text{dip}}$. Here the Cherenkov angle $\theta_c$ is fixed at 47.5° and $\phi_c = 0$ is set at the direction of the particle projected on the radiator plate.](image3)

![Fig. 4. Focussing DIRC for the end-cap region of collider experiments: Sample Design No. 1.](image4)
transmittance even in the UV band where Cherenkov light is intense [13,14].

The number of Cherenkov photons is given as a function of wavelength by the following formula [15]

\[ N(\lambda_2 > \lambda > \lambda_1) = 2\pi\alpha \left( \frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \left( 1 - \frac{1}{(n\beta)^2} \right) , \]

where \( \alpha \) is the fine structure constant.

The loss of photons at each step of photon transportation is given in Table 1 for Sample Design No. 1: the loss averaged between 250 and 600 nm is in fact negligible in the synthetic quartz plate and -6% in the 2.5 m fiber. For quartz, the index of refraction \( n \) varies significantly in the UV band and the image sharpness deteriorates significantly as shown in Fig. 6. The image sharpness is traded off for the number of photoelectrons. The readout pixel size (the size of fiber bundles coupled to one photon sensor) and the quality of the focussing system are then matched to the compromised image sharpness.

### 3.1. Cherenkov radiator disk

The maximum size of synthetic quartz plates commercially available is \( \sim 1 \text{ m} \) (diameter) at present [14]. The radiator of the size of Sample Design No. 1 can only be made by gluing several pieces. We note here in this regard that UV transparent epoxy is available [16]. Cherenkov photons cross the glue joints no more than three times. Thus the entire radiator can easily be made transparent for photons of wavelength longer than 250 nm. We also note

<table>
<thead>
<tr>
<th>No. of emitted photons</th>
<th>1162</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda = 250-300 \text{ nm} )</td>
<td>340</td>
</tr>
<tr>
<td>( \lambda = 300-400 \text{ nm} )</td>
<td>414</td>
</tr>
<tr>
<td>( \lambda = 400-600 \text{ nm} )</td>
<td>408</td>
</tr>
<tr>
<td>Trapped in fibers</td>
<td>6.5-13%</td>
</tr>
<tr>
<td>Trapped after loss in radiator</td>
<td>98%</td>
</tr>
<tr>
<td>Trapped after loss at two mirrors</td>
<td>85%</td>
</tr>
<tr>
<td>Radiator to fiber</td>
<td>60%</td>
</tr>
<tr>
<td>Radiator to fiber</td>
<td>94%</td>
</tr>
<tr>
<td>PMT cathode Q.E.</td>
<td>21.5%</td>
</tr>
<tr>
<td>Final no. of photoelectrons</td>
<td>7-13</td>
</tr>
<tr>
<td>No. of fibers</td>
<td>( \sim 100 \text{ k} )</td>
</tr>
<tr>
<td>Pixel size ( (\theta_c \times \phi) )</td>
<td>1° ( \times ) 3°</td>
</tr>
<tr>
<td>Number of pixels per PMT</td>
<td>5 pixels tied every ( \Delta \theta_c - 8° )</td>
</tr>
<tr>
<td>Number of PMTs</td>
<td>( \sim 750 )</td>
</tr>
</tbody>
</table>

Thus the entire radiator can easily be made transparent for photons of wavelength longer than 250 nm. Table 1 shows the number of photons for Sample Design No. 1 in 20 mm of quartz. (Quartz: \( n = 1.48, \theta_c = 47.5°, \) sensor: PMT, fiber: FEP clad quartz, 1 mm \( \phi, 2.5 \text{ m} \) long.)

Cherenkov images of 3.5 GeV/c pions and kaons for Sample Design No. 1 traversing at \( R = 600, 800, 1000, \) and 1200 mm. The average numbers of photoelectrons \( (N_{pe}) \) are 17, 13, 10.5, and 9.5, respectively.
here that this transparency is expected to persist after a few Mrad of radiation [17].

3.2. Focussing optics

Cherenkov photons fan out from the source points distributed along the particle track and reach the focal surface at various angles both in projection onto the radiator plate (the $x$ coordinate in Figs. 2 and 6) and in the direction perpendicular to it (see Figs. 2, 5, and 6). Optics is arranged so that photons are focussed in the $y$ direction and hit the surface approximately normal (see Fig. 5). Note that photons are not focussed in the $x$ direction.

The forward end-cap region covers only a limited solid angle in most collider experiments, corresponding typically to $\theta_{\text{max}} = 15-30^\circ$ for high momentum particles. In Sample Design No. 1, the focal surface is approximated by a cylindrical surface and its optical parameters are: a toroidal mirror surface with major and minor radii of 400 and 257 mm respectively; a cylindrical focal surface with radius of 530 mm.

Parallel light rays emitted by $\beta = 1$ particles with $\theta_{\text{dirp}} = 15, 20, 25$, and $30^\circ$ are traced in Fig. 5 for $\theta_{\text{c}} = 47.5^\circ$. The toroidal mirror surface is coated with aluminum and its reflectance is about $\sim 92\%$ for the wavelength range between 250–600 nm (see Table 1).

3.3. Fiber readout

In Sample Design No. 1, the image is captured by the quartz fibers on the focal plane. Because photons are not focussed in the $x$ direction, the entrance angle, the angle a photon makes to the fiber axis, increases as the propagation direction deviates from the major radius of the toroid. If the entrance angle exceeds a limit $\theta_{\text{max}}$, photons are not transported to the photon sensor: this limits the total number of photons transported to phototubes. The angle $\theta_{\text{max}}$ is determined by the refractive indices of the core and clad of the optical fiber. In the standard communication fibers, the minimum practical ratio of the two refractive indices $(n_{\text{clad}}/n_{\text{core}})$ is around $0.985$, corresponding to Numerical Aperture $(\text{NA} = \sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2})$ of $0.25$ or $\theta_{\text{max}} = 9.94^\circ$ at $\lambda = 633$ nm [13]. The quartz fibers with hard polymer, silicone, or FEP clad will have $\theta_{\text{max}} \approx 14.5^\circ$ $(\text{NA} = 0.37)$, $16.2^\circ$ $(\text{NA} = 0.41)$, or $23.3^\circ$ $(\text{NA} = 0.58)$ at $\lambda = 633$ nm [13]. Note that the maximum angle will be much larger if photons enter the same fiber from air or material with a lower refractive index. If fibers are air-clad, $\theta_{\text{max}}$ will be $46.7^\circ$ $(\text{NA} = 1.06)$. This $\theta_{\text{max}}$ determines the length (in $x$) of the arc-like image detectable by photons sensors.

Another important parameter in capturing photons is the packing fraction, the ratio of the total core aperture of fibers to the total focal surface area. This is determined by the radius of the core and the thickness of the clad. For the fibers mentioned above, the typical core diameter will be 600–1000 $\mu$m and the clad thickness 10–25 $\mu$m [13]. If circular fibers are tightly packed without clad, the packing fraction reaches 87%.

The fiber assumed in Sample Design No. 1 is cladded with FEP and has core diameter of 1000 $\mu$m, clad thickness of 25 $\mu$m and $\theta_{\text{max}}$ of $23.3^\circ$. The design, as well as all other designs presented here, assume a random pack of the FEP-cladded fibers with packing fraction of 60%.

In the focussing block of the design, the fiber diameter corresponds to about half of the image width and one readout pixel consists approximately of 30 fibers in the $x$ direction by 2 fibers in the $y$ direction, or $1.5^\circ$ in $\phi_{\text{c}}$ by $1^\circ$ in $\theta$. The number of phototubes can be reduced by combining several readout pixels separated by $\theta_{\text{c}} \gg 1^\circ$ if confusion can be avoided. To cover the $\theta_{\text{c}}$ range of $17-33^\circ$ and the entire $x$ coordinate $(\phi_{\text{c}} = 360^\circ)$ in Sample Design No. 1, about 100 k fibers and 750 photomultiplier tubes are required.

3.4. Photomultiplier tubes

The number of photoelectrons limits the performance of the focussing DIRC. The photomultiplier tube therefore needs to have a high quantum efficiency in the UV and blue bands (250–400 nm) and to be capable of detecting single photoelectrons with a high efficiency. The typical peak quantum efficiency of UV-glass window phototubes used in Sample Design No. 1 and the prototype device [18] is $\sim 27\%$, while the averaged one over the spectrum of photons transported to phototubes is $\sim 22\%$.

The resolution of the image position in the $y$ coordinate depends on the intrinsic image sharpness, the pixel size, and the number of photoelectrons $(N_{\text{pe}})$. The Intrinsic image sharpness is primarily determined by chromatic dependence of the Cherenkov angle $(\theta_{\text{c}})$. The multiple Coulomb scattering of the charged particle in the radiator, and measurement error on the particle track. The Cherenkov ring images (or arcs) shown in Fig. 6 have been produced by Monte Carlo simulations of Sample Design No. 1 and give angular resolutions $\delta \theta_{\text{rms}} \approx 0.45/\sqrt{N_{\text{pe}}}$.

Several high quality segmented photon sensors, operational in strong magnetic field (0.5–1.5 T), have become available. They include fine-mesh phototubes, micro-channel plate tubes with GaAsP photocathode, and hybrid avalanche photodiodes [19]. If their physical size permits, they can be mounted directly on the focal plane, eliminating bulky fiber bundles. Their quantum efficiency is, however, only comparable to that of the phototubes mentioned above [18]. Visible Light Photon Counter (VLPC), on the other hand, has nearly three times higher quantum efficiency at around 400 nm and is capable of detecting single photons with excellent signal-to-noise ratio [12]. For moderate magnetic field (<1 kG) newly developed miniature tubes [20] can also be used. These
new photon sensors will enhance the potential and flexibility of the focusing DIRC, as will be discussed later.

4. Expected performance: Sample Design No. 1

4.1. Photoelectron yield

The average number of photoelectrons expected in the photomultiplier tube array for a $\beta = 1$ particle per 1 cm track length in quartz is given as a function of the photon wavelength in Fig. 7 and Table 1. The photoelectron yield depends also on the impact point, direction, and velocity of the particle. Of these, the position dependence makes significant effects. For the focusing optics of the design, fibers accept a larger fraction of photons when the photon path is longer. This is because light rays approach the radial direction and are more likely to be accepted within $\theta_{\text{max}}$ of quartz fibers. For example we get about 17, 13, 10.5 and 9.5 photoelectrons in average at locations $R = 60, 80, 100,$ and 120 cm, respectively, for Sample Design No. 1 (see Fig. 6).

4.2. Expected $\pi$–$K$ separation

The position of the Cherenkov ring in the y-coordinate is determined by fitting the measured distribution of photoelectrons with the known image shape. Fig. 8 shows the separations of the pion and kaon images in the y-coordinate ($\pi$–$K$ separation) for the images given in Fig. 6 for particles crossing at $R = 800$ and 1200 mm: they are separated by about 3.8σ and 3.3σ respectively at 3.5 GeV/c.

As the kaon momentum decreases, the Cherenkov ring ceases to reach the focusing block: this limit depends on the crossing point and is around 0.5–1.0 GeV/c. Down to this limit, we expect to see the Cherenkov ring and make positive identification of kaons and pions. Below this momentum, the device will continue to see pion rings and work as a localized threshold Cherenkov counter identifying kaons by the absence of the Cherenkov ring.

5. Other sample designs

The focusing DIRC can be designed many other ways than Sample Design No. 1. To cover the forward region of collider experiments or fixed target experiments, one may configure a circular radiator with a focusing block attached on its outer circumference, as will be shown below. Since the incident angle Cherenkov photons make to the fiber axis decreases in average in the outer radius readout scheme, we expect substantially more photoelectrons than for the inner radius readout scheme of Sample Design No. 1. This merit needs to be balanced against increase in the number of pixels to be read out.

Although not yet worked out as a design in this paper, we believe the radiator can take a cylindrical shape. Such a focusing DIRC will be ideal to cover the barrel region of compact collider experiments or the large angle region of fixed target experiments.

The focusing block can also be designed in many different ways. It can be segmented into several pieces and attached anywhere along the periphery of the radiator. To facilitate attachment of fibers or photon sensors, Cherenkov photons can be reflected more than once in the focusing block: the double reflection focusing scheme presented in this section brings the focal surface planar and facing outward.
5.1. Outer radius readout scheme

The inner radius readout scheme exemplified by Sample Design No. 1 has several advantages. The most important one is that it does not leave any dead space between the barrel and the endcap regions. The second advantage is that the number of readout channels is reduced to about a half when compared with the outer readout scheme. These advantages are balanced by the decrease in the photoelectron number as can be seen in Fig. 6 and Table 1. When higher momentum particles are to be separated or when a higher particle density is expected, the design will probably begin to fail.

Number of photons is followed stepwise in Table 2 for an alternative scheme (Sample Design No. 2) where the focussing block is placed at outer radius. Sample Design No. 2 has the same dimension as No. 1 but for the position of the focussing block. The percentage of photons accepted to the fibers nearly doubles and the loss in the reflection at the outer radius is eliminated for this outer radius readout scheme. The increase in the fiber acceptance is due to the fact that the angle the Cherenkov photon makes to the fiber axis decreases in average for the outer radius readout. Images of the Cherenkov rings shown in Fig. 9 correspond to those shown in Fig. 6 for Sample Design No. 1. One can see that a larger portion of the ring is captured because of increase in the fiber acceptance. In the collider experiment where most of signal cables, electric power lines, cooling water pipes, and liquid helium tubes are fed between the barrel and endcap regions, the outer readout scheme may be difficult to accommodate. In most fixed target experiments and extreme forward regions of collider experiments, however, the outer readout scheme is more desirable since kaons will be separated from pions to much higher momenta. Fig. 10 shows the expected π–K separation for Sample Design No. 2. We expect 33–54 photoelectrons and kaons can be separated from pions by 5.6–7.4σ at 3.5 GeV/c.

As the circumference increases, so does in principle the number of readout channels. If one gets more photoelectrons than needed, portions of the focal surface may be left out without fibers or sensors.

5.2. Readout with VLPC – a design for higher momenta

The important advantage of using the focussing DIRC as a particle identification device is that detected photons are...
concentrated to a narrow arc. The width of the arc is determined mostly by dispersion in the refraction index in the UV to blue range. The width of the Cherenkov ring image will be reduced by a large factor if the number of photoelectrons permits to filter out the UV and blue band, for example $\lambda < 400$ nm.

Quite recently, the visible light photon counter (VLPC) has become commercially available [12]. VLPC has very high quantum efficiency for $\lambda = 400$–$800$ nm as shown in Fig. 11 and will be used in large quantities to read out scintillation fiber trackers of CDF and D0 experiments at Fermi Lab. [21]. The device needs to be cooled to around 7 K but the handy cassette type housing developed for the two experiments simplifies its use [22]. The enhanced quantum efficiency and the UV cutoff of VLPC matches perfectly to our need. Sample Design No. 3 shown in Fig. 12 is read out at the outer radius by $d = 0.5$ mm fibers and VLPCs. The number of converted photoelectrons is plotted as a function of the photon wavelength in Fig. 13. The images and separations of Cherenkov rings for pions and kaons crossing at several positions of Sample Design No. 3 have been generated by Monte Carlo simulations as given in Figs. 14 and 15, respectively.

From the simulation studies presented in Fig. 15, we expect the focussing DIRC read out with VLPCs will separate kaons from pions up to $\sim 10$ GeV/c. In the outer radius readout scheme, the device is fully active to the inner rim. Combined with the fact that the synthetic quartz is extremely resistant to radiation damage, the focussing DIRC read out from the outer radius with VLPCs will be a good candidate for the particle identifier in the forward arm of hadron colliders.

5.3. Double reflection focussing scheme

In Sample Designs No. 1, 2, and 3, the focal surfaces are curved and face towards inside of the focussing block (Figs. 5 and 12). In this geometry, routing fibers out of the magnetic volume may interfere with other detector components. To avoid this, we have devised a design in which Cherenkov photons are reflected twice to make the focal surface almost planar and face axially outwards as shown in Fig. 16. About 8% of photons will be lost at the additional reflection.

6. Comparison with the non-focussing DIRC

The focussing DIRC has several advantages over the non-focussing DIRC [5–7]. The most important one is that the focussing part of our design is embedded in the extension of the radiator plate, occupying no more than 10–12 cm by 10–12 cm in cross section. The focussing DIRC enables one to make a compact particle identification device that fits into tight detector configurations and to
reduce the overall detector size significantly (Fig. 4). The photon sensors can be placed either directly on the focal surface or outside the magnetic volume of the detector.

The second important advantage is that detected photons are concentrated in a narrow arc in the focussing DIRC and the ring reconstruction involves much less phototubes. The end-cap design to read out from the inner radius (Sample Design No. 1), for example, is an elegant scheme in that the readout elements can be reduced to ∼100 k fibers (1 mm φ) and 750 phototubes (UV window, 1 in. φ).

The focussing DIRC provides uniform coverage with imaging capability while non-focussing DIRC leaves typically 5% insensitive area spread over the detector. This complete coverage makes the focussing DIRC an excellent threshold Cherenkov counter even below the kaon threshold.

The fourth and probably the most important advantage in the future is that the focussing DIRC will be capable of separating kaons and pions at around 10 GeV/c (Fig. 15). In the focussing DIRC, the photon acceptance angle of quartz fibers limits the captured fraction of Cherenkov photons to about 7–15%, a half of the fraction for the non-focussing DIRC (Tables 1 and 2). This loss of photons is compensated by making use of UV photons (∼250 nm) transported in high-purity synthetic quartz [14] all the way to the photon sensors (Fig. 7), or by using higher quantum efficiency devices such as VLPC (see Section 5.3). In the non-focussing DIRC, on the other hand, photons are lost primarily while propagating through the quartz bar.

7. Results from the prototype test

We made a prototype device that represents the most essential part of the focussing DIRC (Fig. 17). The radiator is a synthetic quartz plate 21 × 22 cm² in area and 2 cm in thickness and the focussing block has a section of a toroid with outer and inner radii of 500 and 420 mm respectively, and with focal length of 160 mm. The three bundles of ∼118 quartz fibers (φ = 1000 μm) with hard polymer clad (r = 50 μm, θmax = 14.7° at λ = 633 nm) attached to the focal plane were read out by 35 phototubes (Hamamatsu...
The fiber bundles covered only ~44% of the Cherenkov arc image to be captured as shown in Fig. 18.

The device was tested with 950 MeV electrons from the Electron Synchrotron at Institute for Nuclear Study, Univ. of Tokyo. The beam was defined by three plastic scintillation counters to ±0.42° and the prototype device was set at ~10° to the beam so that the Cherenkov image appears as shown in Fig. 18.

In average we measured 5.3 photoelectrons where the 10.3 photoelectrons were expected. We could not quantify where the unexpected loss of 47% occurred but made qualitative estimates: the largest loss was at the glue joints of the plastic-clad fibers to the focal surface where fluid EpoTek 305 [16] permeated between the clad and the core. In such fibers (about ~35%), most of the transported photons are lost. We believe this can be avoided in future work. We calculated the image position, assuming its shape, out of the detected photons event by event. Its distribution is shown in the left half of Fig. 19.

The measured width of the Cherenkov ring image (the left half of Fig. 19) reflects the beam divergence, the multiple scattering in the radiator plate, and the intrinsic width of the image. Since the beam divergence is most uncertain of the three, we calculated the intrinsic width from the dispersion of the detected photons in the vertical position (see Fig. 19) event by event. Its distribution is
shown in the left half of Fig. 20. From these measurements we extracted the intrinsic width of the ring in the prototype device to be ~0.28° (rms) for the wavelength coverage of 250–600 nm.

7.1. Comparison with Monte Carlo simulations

In the simulations program, Cherenkov photons were generated along the particle trajectory, effectively including the spectral dependence, the attenuation in the quartz and fiber, the phototube quantum efficiency, the beam divergence, and the multiple scattering. These photons were then ray-traced from the entrance to the fiber array. If a photon entered a fiber core within $\theta_{\text{max}}$, we considered it to be detected. Since the measured number of photoelectrons was only 53% of Monte Carlo expectation (probably due to the faulty glue work described before), we randomly left out 47% of the MC generated photoelectrons to obtain the right halves of Figs. 19 and 20.

The most bias-free comparison between the measured image and the Monte Carlo expectation can be made from the two distributions in Fig. 20. We conclude from Fig. 20 that the Cherenkov photons can be transported to the focussing block and then focussed to an arc-like image about 0.36–0.38° wide (rms) for the spectral range of the phototube (250–600 nm). This implies that the image position (e.g. the centroid of the image) can be determined to about $\sim (0.36–0.38)/\sqrt{N_{\text{ph}}}$ In reality, multiple scattering and track determination error will make the width a little wider.

8. Conclusion

A new compact Cherenkov ring imaging device potentially capable of separating kaons and pions in the multi GeV/c range has been proposed. Since the radiator is a thin synthetic quartz plate (planar or curved), the device can be designed to fit into most detector configuration and harsh-radiation environment. We have demonstrated the most essential principle of the device that the internally reflected Cherenkov ring can be focussed to a narrow arc by building a prototype and exposing it in an electron test beam. The obtained image width is consistent with our expectation based on Monte Carlo simulations.

The potential of the focussing DIRC as a particle identifier will be best exploited when a large fraction of the Cherenkov ring can be imaged, as in $e/\pi/K/p$ separation in multi GeV/c fixed target experiments, $e/\pi/K/p$ separation in the forward arms of sub-TeV hadron collider experiments, and $e/\mu/\pi$ separation in stopped K-decay experiments. If photon sensors with a higher quantum efficiency such as VLPCs [12] are used, the device will be able to separate pions and kaons up to ~7–10 GeV/c, and muons and pions up to ~1 GeV/c with minimum spatial requirement (<3 cm).

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[17] SUPRASIL-P30 has not degraded its transmittance up to $4 \times 10^{16}$ thermal neutrons per cm$^2$ nor up to $5 \times 10^{15}$ electrons (0.75 MeV) per cm$^2$ according to Shin-Etsu Quartz Products Co. Ltd. [14].
[18] For example, R1398 (used in the prototype device), R4125, and R5800 by Hamamatsu Photonics K.K.
[19] The UV window fine mesh phototube by Hamamatsu Photonics, R3506 (1 in. $\phi$, quantum eff. ~ 22%), the GaAsP multi-channel plate tube with UV window by Intevac (1 in. $\phi$, quantum eff. ~ 27%), and the hybrid avalanche photodiode by API (1 in. $\phi$, quantum eff. ~ 25%).
[20] For example, R5600 series by Hamamatsu Photonics K.K.
[22] Cassette dewars with an array of 8–16 VLPCs have already been produced and even larger ones are under construction for the scintillation fiber readout;
M. Atac and A. Bross, private communication (1996).