A new type of Time-Of-Propagation (TOP) Cherenkov detector for particle identification*

YAN Jie(言杰)1) SHAO Ming(邵明)2) LI Cheng(李澄)

(Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China)

Abstract A new type of particle identification (PID) detector based on measurements of 1-D Time-Of-Propagation (TOP) and 1-D space information is described. Geant4 toolkit is used to simulate the propagation of Cherenkov photon in thin quartz bar radiator. Contributions to the timing uncertainty are discussed. The π/K separability (S_0) is defined and its dependence on the particle momentum, incident angle and propagation length are studied, respectively.

Key words Time-Of-Propagation, particle identification, Cherenkov detector

PACS 29.40.Ka, 29.40.Mc

1 Introduction

The Time-Of-Propagation (TOP) Cherenkov detector is a novel technical extension of the Detection of Internally Reflected Cherenkov (DIRC) light for particle identification. In contrast to the BarBar DIRC[1—3], which provides the 2-dimensional spatial coordinates of the photons on a projection plane with a large detector volume, it measures both the TOP information of Cherenkov photons in the quartz radiator bar and their position information at the bar end. Thus TOP has the advantage of being simple in construction, compact in size and quick in time response. It is proposed to be used in the internal target experiment on the Cooling Storage Ring (CSR) at Lanzhou, China[4]. In our simulation, the TOP Cherenkov detector comprises a long quartz bar as the Cherenkov radiator and photon's light guide, with a length of 1000 mm, width of 200 mm and thickness of 20 mm. A total reflection mirror is attached at the backward-end surface, while position sensitive photo-multipliers (PMT) with high time resolution are coupled to the forward-end surface (with silicone oil). Fig. 1 illustrates the principal structure of the TOP detector in the (x, y, z) coordinate system. The TOP detector thus measures both the TOP and x-position information of the Cherenkov photons produced by different particle species to reconstruct the Cherenkov angle. When a charged particle passed through the radiator bar, Cherenkov photons are emitted in a conical direction defined by the emission angle (θ_c), meeting the relation $\cos\theta_c = 1/n\beta$, where n is the refraction index, and β is the particle velocity (in unit of the speed of light in vacuum). Photons propagate to both ends (backward and forward) by means of total reflection on the internal bar surface while the backward photons are reflected by the total reflection mirror at the end-bar. Photons are collected by the position-sensitive multi-anode phototube at the forward-end.

Received 8 July 2008

* Supported by National Natural Science Foundation of China (10575101,10675111) and the CAS/SAFEA International Partnership Program for Creative Research Teams (CXTD-J2005-1)

1) E-mail: yanjie@mail.ustc.edu.cn

2) E-mail: swing@ustc.edu.cn

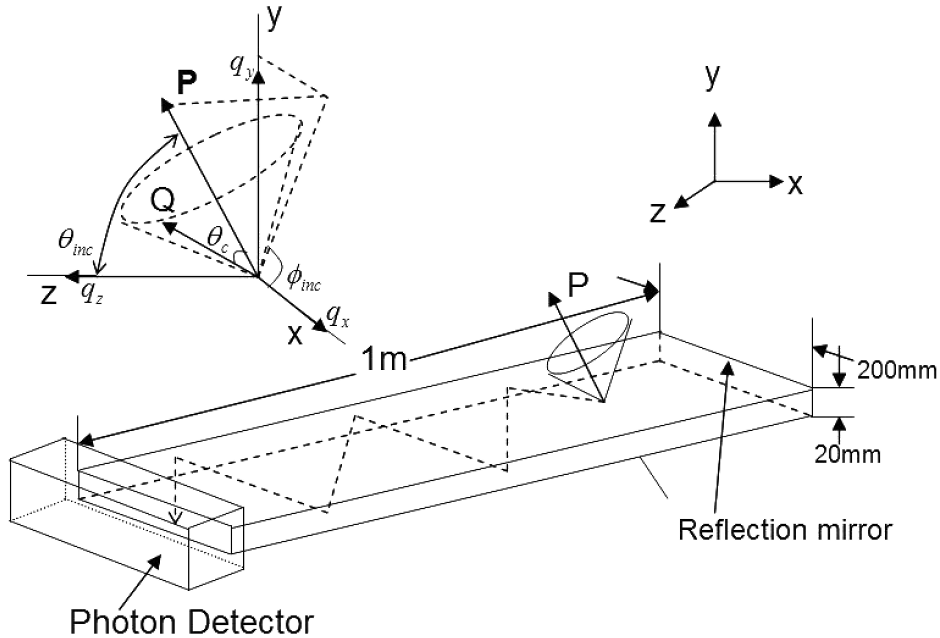

Fig. 1. structure of the TOP detector in our simulation.

2 Time uncertainty

The relationship between these measured quantities and the Cherenkov angles is described below[1, 4]. Considering a local frame where the charged particle moves along the (z) axis, the direction components of the Cherenkov photon emission in this frame $(q_{x'}, q_{y'}, q_{z'})$ are related to the Cherenkov angles as

$$\begin{aligned} q_{x'} &= \cos\phi_c \sin\theta_c, \\ q_{y'} &= \sin\phi_c \sin\theta_c, \\ q_{z'} &= \cos\theta_c. \end{aligned} \tag{1}$$

Then in the right-handed coordinate system attached to the bar frame, when the track polar and azimuthal angles of an incident charged particle are $\theta_{\rm inc}$ and $\phi_{\rm inc}$ (see Fig. 1), respectively, the direction components of the photon emission in the bar frame (q_x, q_y, q_z) can be written as

$$\begin{aligned} q_x = {}& q_{x'}\cos\theta_{\rm inc}\cos\phi_{\rm inc} - q_{y'}\sin\phi_{\rm inc} + \\ & q_{z'}\sin\theta_{\rm inc}\cos\phi_{\rm inc}, \\ q_y = {}& q_{x'}\cos\theta_{\rm inc}\sin\phi_{\rm inc} + q_{y'}\cos\phi_{\rm inc} + \\ & q_{z'}\sin\theta_{\rm inc}\sin\phi_{\rm inc}, \\ q_z = {}& -q_{x'}\sin\theta_{\rm inc} + q_{z'}\cos\theta_{\rm inc}. \end{aligned} \tag{2}$$

Relying only on the z-component of the light velocity in the quartz bar, the TOP can be simply expressed as

$$t_{\rm p} = \left(\frac{L}{c/n(\lambda)}\right) \times \left(\frac{1}{q_z}\right), \tag{3}$$

where L is the distance from the particle's incident point to the PMT along the bar axis (z-axis), $n(\lambda)$ is the refraction index at wavelength , c is the light velocity in the vacuum, and q_z is the directional z-component of photon emission. If we fix $\theta_{\rm inc}$ and $\phi_{\rm inc}$, q_z is a function of θ_c and ϕ_c. The ϕ_c angle of Cherenkov photons is uniform over 2π, and can be calculated by using the TOP and x-position information. Thus, the θ_c information of different particle with the same momentum can be provided.

Taking the structure of the TOP detector in the simulation into account, we estimate various contributions to the accuracy of the PID measurement in three parts, as shown below.

(1) The wavelength dependence of the refractive index: Considering the quantum efficiency of the phototube and the λ-dependence of the Cherenkov photon yield, the effect to TOP is

$$\frac{\sigma_{t_{\rm p}}}{t_{\rm p}} = \left(\frac{\sigma_n}{n}\right) \times (1-\alpha), \tag{4}$$

where

$$\alpha = n \times \left(\frac{\partial q_z/\partial n}{q_z}\right). \tag{5}$$

In our simulation, we take $n = 1.47 \pm 0.008$ ($\Delta n/n = 5\times10^{-3}$) for this effect. Making use of the Eq. (3),

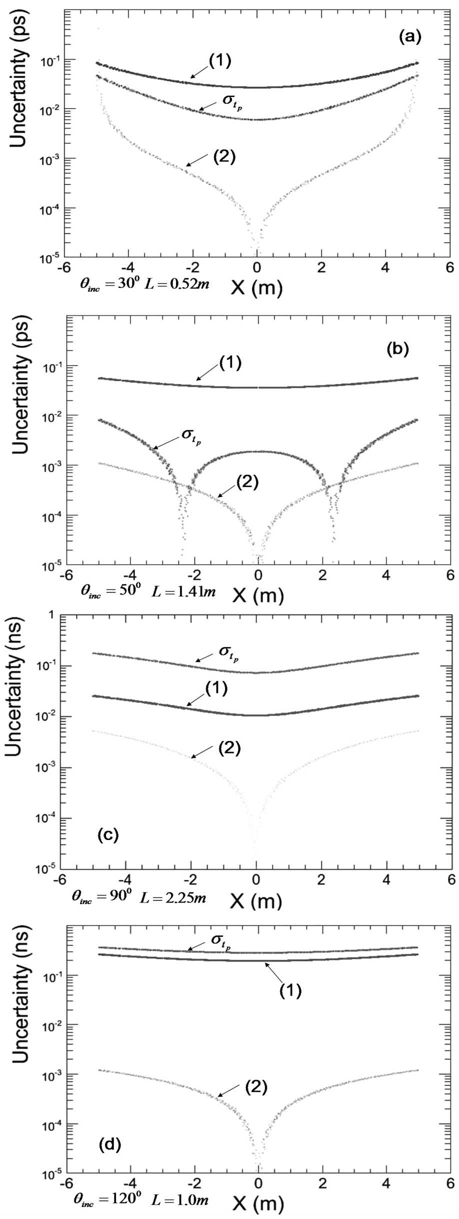

Fig. 2. the expected time uncertainties along the expanded x-position from part (1) and (2) for 4 different conditions and t_p differences between π and K, σ_{t_p}.

the result is

$$\sigma_{t_\mathrm{p}} = \left[\frac{2\cos\theta_\mathrm{c}\cos\theta_\mathrm{inc}+\cos\phi_\mathrm{c}\sin\theta_\mathrm{inc}\sin\theta_\mathrm{c}(\mathrm{ctg}^2\theta_\mathrm{c}-1)}{(-\sin\theta_\mathrm{c}\cos\phi_\mathrm{c}\sin\theta_\mathrm{inc}+\cos\theta_\mathrm{c}\cos\theta_\mathrm{inc})^2}\right]\times 4.9\times L\times\left(\frac{\sigma_n}{n(\lambda)}\right). \quad (6)$$

(2) The hit position resolution: The hit position resolution depends on the anode width of phototube. Since the phototube in our simulation has a 1.0 mm anode width, the x-position resolution is evaluated as $\sigma_x \approx 1.0$ mm. Making use of the error transfer formula, the time uncertainty is:

$$\sigma_{t_\mathrm{p}} = \frac{4.9L\sin\theta_\mathrm{c}\sin\theta_\mathrm{inc}\sin\phi_\mathrm{c}\sigma_\mathrm{x}}{4.9Lq_z\sin\theta_\mathrm{c}\cos\theta_\mathrm{inc}\sin\phi_\mathrm{c}(\cos\phi_\mathrm{c}+1)+q_x\sin\theta_\mathrm{c}\sin\theta_\mathrm{inc}}. \quad (7)$$

(3) The transit time spread (TTS) of the phototube, the timing jitter due to the start signal determination, the quartz thickness and the charged particle tracking accuracy are included to make an effective contribution of $\sigma_{t_\mathrm{p}} \approx 80$ ps[5].

Taking π and K with a momentum of 4 GeV/c for example, the expected individual time uncertainty of items (1) and (2) are shown in Fig. 2. The t_p difference between π and K, σ_{t_p}, is also shown. Various conditions of the incident angle are considered here. On the other hand, the length L here is not real, but hypothetical, only for discussion purposes. The magnetic field is not considered. If the σ_{t_p} is smaller than the sum of the time uncertainty of effect (1) and (2), it's not possible to identify π and K in this condition. Otherwise π and K can be identified by using this (TOP) method.

3 PID performance of TOP

Now, from previous discussions of the time uncertainty, the π/K separability is defined in order to estimate the PID performance.

$$S_0 = \sqrt{\left\{\sum_i\left(\frac{(\sigma_{t_\mathrm{p}})^i}{(\sigma_\mathrm{T})^i}\right)^2\right\}\cdot\kappa}\ , \quad (8)$$

where σ_{t_p} is the t_p differences between π and K, σ_T is the total time uncertainty arising from the discussion above. The summation includes each Cherenkov photon hitting the PMT. κ is the detected portion of generated Cherenkov photons in the simulation.

Expected S_0 dependence on particle momentum is shown in Fig. 3(a), for three different polar angles (θ_inc). The separability is exponential decrease along with the increment of momentum. Only forward photons are considered here. In Fig. 3(b), in the regions of $\theta_\mathrm{inc} \leqslant 90^0$ and $\theta_\mathrm{inc} \geqslant 90°$, the forward photon and backward photon are considered, respectively, which are indicated by the solid and dotted line. It shows the resultant as a function of the polar angle (θ_inc) for three different momentums. The separability is worst at $\theta_\mathrm{inc} = 50°$ which is due to the destructive correlation between θ_inc and θ_c , as mentioned above.

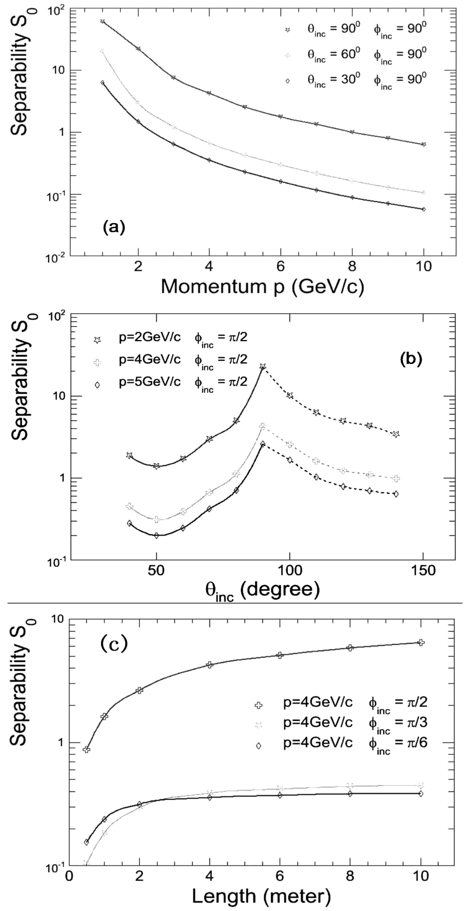

Fig. 3. the expected time uncertainties along the expanded x-position from part (1) and (2) for 4 different conditions and $t_{\rm p}$ differences between π and K $\sigma_{t_{\rm p}}$.

The relation between S_0 and propagation length is shown in Fig. 3(c). S_0 increases rapidly when the propagation length is less than 2 m, then increases slowly and tends to saturate at longer propagation length.

4 Discussion and summary

We have introduced a new type TOP Cherenkov detector based on the measurement of 1-D time of propagation of the Cherenkov photon and the 1-D position information. Since it only needs 1-D position information (in contrast to the DIRC and the gas Cherenkov imaging detector), the quantity of PMT can be reduced enormously on the one hand, so as to the construction cost. On the other hand, it can be constructed more compact and needs less space. Combining to the geometrical construction of TOP, we have discussed various contributions to the time uncertainty. In some cases that the total time uncertainty is large than the time of propagation difference between difference particles with the same momentum, TOP Cherenkov detector can not identify those particle. We defined the separability between π and K. Its dependence on the particle momentum, incident angle and propagation length, are discussed respectively. More detailed woke is needed in the future.

References

1 Adam I, Aleksan R et al. Nucl. Instrum. Methods A, 1997, **433**: 121

2 Adam I, Aleksan R et al. Nucl. Instrum. Methods A, 2005, **538**: 281

3 Staengle H et al. Nucl. Instrum. Methods A, 1997, **397**: 261

4 XIAO Z G. Talk Presented at QM2006, Shanghai

5 Akatsu M, Aoki M et al. Nucl. Instrum. Methods A, 2000, **440**: 124