A DIRC-like time-of-flight detector for the experiment at the Super Tau-Charm Facility

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Abstract

The Super Tau-Charm Facility (STCF) is a future electron-positron collider proposed in China with a peak luminosity of above 0.5×10^{35} cm^{-2}s^{-1} and center-of-mass energy ranging from 2 to 7 GeV. Excellent particle identification (PID) capability is one of the most important requirements for the detector at the STCF. A 3σ π/K separation up to 2 GeV/c is required within the detector acceptance. A DIRC-like time-of-flight (DTOF) detector is proposed to meet the PID requirement for the endcap region of the STCF. The conceptual design of the DTOF detector and its geometry optimization is presented. The PID performance of the detector has been studied with Geant4 simulation. With a proper reconstruction algorithm, an overall time resolution of \sim 50 ps can be achieved for the detector with an optimum geometry, when convoluting contributions from all other sources, including the transit time spread (TTS) of photodetector, electronic timing accuracy, and an assumed precision (\sim 40 ps) of the event start time. And a better than 4σ π/K separation power at the momentum of 2 GeV/c is achieved over the full sensitive area of DTOF detector, fulfilling the physics requirement for the PID detector of the experiment at the STCF.

Keywords: DIRC, TOF, Cherenkov detector, Super Tau-Charm facility, STCF, PID

1. Introduction

The Super Tau-Charm Facility (STCF, [1-2]) is a future high-luminosity electron-positron collider proposed in China, which would operate in a center-of-mass energy region ranging from 2 to 7 GeV with a peak luminosity of >0.5×10^{35} cm^{-2}s^{-1}. The energy region covered by the STCF lies in the transition interval between non-perturbative quantum chromodynamics (QCD) and perturbative QCD, enabling a rich physics program including τ and charm physics, hadron physics, and new physics searches.

Excellent particle identification (PID) capability is a crucial demand on detector
performance driven by the physics program at the STCF. According to physics case studies for the STCF, a statistical separation power better than 3σ between charged hadrons (π±, K±, and p/̅p) with momentum up to 2 GeV/c is required within the full detector acceptance [2]. In the physics research at STCF, charged hadrons at low momentum can be identified with the characteristic ionization energy loss (dE/dx) by the tracking detector. However, at higher momentum, a dedicated PID detector is needed to accomplish the required particle separation capability. The PID detector is also required to cope with the high radiation level and counting rate anticipated in the high luminosity condition at the STCF. Therefore, it should have a fast response and good radiation resistance. Besides, the material budget of PID detector should be kept as low as possible to minimize its impact on the energy measurement of photons with the electromagnetic calorimeter (EMC) outside the PID detector. Lastly the PID detector should be sufficiently compact to be accommodated in rather limited space between the tracking detector and the EMC.

At the STCF detector, because of the limited distance from the interaction point to the barrel of the PID detector, the usual time of flight (TOF) method wouldn’t work for the barrel region given the required particle identification capability. And the Ring Imaging Cherenkov detector (RICH, [3]) is a good candidate for the barrel PID detector. But due to extended distance from the interaction point to the endcap PID detectors, a TOF detector with a very high intrinsic time resolution and fast response becomes a viable option for the endcap PID detector. The concept of Detection of Internal total-Reflected Cherenkov light (DIRC, [4]) offers a solution to such a detector. And a DIRC-like time of flight detector (DTOF) is proposed as the endcap PID detector at the STCF experiment due to its compact structure, simplified operation and maintenance, high rate capability and high radiation tolerance, as well as excellent timing performance.

2. DTOF detector concept

The concept of DIRC was first introduced by the Babar experiment [5-6]. In this concept, Cherenkov photons generated in the long fused silica bar are propagated to one end through total internal reflections, then projected to an array of photo sensors via an expansion water volume. The fused silica bar is taken as both Cherenkov radiator and light guide. The propagation direction of Cherenkov photon is preserved through hundreds of reflections and the spatial pattern of the Cherenkov ring can be recognized for PID purpose. It’s worth noting that the time resolution of Babar DIRC detector for single photon was around 1ns, which was mainly used to suppress uncorrelated background by setting a proper time window. Then the DIRC detectors with very fast timing capability were developed to explore the PID potential of the detectors in the time domain. One example is the imaging Time of Propagation (iTOP) detector at Belle II [7-9] experiment, where the PID performance is primarily driven by precise measurement of the propagation time of Cherenkov photons transmitted in the cuboid-shaped radiator plate. To this end, the two-dimensional position and one-dimensional time of photons hit are measured by an array of photo sensors at one end of plate, with particularly high precision timing resolution. With improved position and time
resolution, some very compact DIRC detectors can be realized and are expected to have better PID capability, such as those proposed in the future PANDA experiment [10-12] and EIC project [13-14]. And the excellent timing capability of the new DIRC detectors has led to the direct application of DIRC technology to high time resolution and high rate TOF measurement, including the FTOF detector proposed for the superB project [15-16] and the TORCH detector being developed for LHCb upgrade [17-18]. And the DTOF detector proposed for the STCF experiment is the latest example of these DIRC-like detectors.

The DTOF detector aims for a total time resolution of 50 ps in TOF measurement so as to provide $3\sigma$ $\pi/K$ separation power up to 2 GeV/c for STCF experiment. It is located in the endcap region of STCF detector and consists of two identical discs positioned 1400 mm along the beam direction away from the collision point. Each disc is made up of some sectors (shown in Fig. 1), with an inner radius of $\sim 560$ mm and an outer radius of $\sim 1050$ mm, covering $\sim 22^\circ$-$36^\circ$ in polar angle $\theta$. In each sector, a synthetic fused silica plate is used as radiator to generate Cherenkov photons. Considering the effect of magnetic field on the photon sensors, an array of multi-anode micro-channel plate photomultipliers (MCP-PMT) are optically coupled to the radiator along the outer side. The whole sector is enclosed in a light-tight black, occupying $\sim 200$ mm space along the beam direction.

Fig. 1. The conceptual design of DTOF. The front (left) and side (right) views of a sector are shown. A fused silica plate is used as radiator, and an array of MCP-PMTs are coupled to the radiator as photon sensor, the whole sector is enclosed in a light-tight black box.

3. DTOF Timing uncertainty analysis

Time resolution is a significant performance for DTOF detector. It is necessary to analyze the factors that affect the timing uncertainty and their relative importance should be studied to optimize the time performance. Similar to the FTOF detector proposed for the superB project, the main sources contributing to the timing uncertainty of the DTOF detector are as follows [15]:

$$
\sigma_{tot}^2 \sim \sigma_{trk}^2 + \sigma_{t0}^2 + \left( \frac{\sigma_{elec}}{\sqrt{N_{p.e.}}} \right)^2 + \left( \frac{\sigma_{TTS}}{\sqrt{N_{p.e.}}} \right)^2 + \left( \frac{\sigma_{det}}{\sqrt{N_{p.e.}}} \right)^2
$$
where $N_{\text{p.e.}}$ is the number of photo-electrons (p.e.), $\sigma_{\text{trk}}$ is the error caused by track reconstruction, $\sigma_{T_0}$ is the event reference time ($T_0$, i.e. when physical collision happens) error mainly affected by the collider design of STCF, $\sigma_{\text{elec}}$ is the electronic timing accuracy, $\sigma_{\text{TTS}}$ is the single-photon transit time spread (TTS) of MCP-PMT, and $\sigma_{\text{det}}$ is the time reconstruction uncertainty of the DTOF detector. From this formula, we can see that the contribution from $\sigma_{\text{elec}}$, $\sigma_{\text{TTS}}$ and $\sigma_{\text{det}}$ will decrease with increasing $N_{\text{p.e.}}$, while the timing errors from $\sigma_{\text{trk}}$ and $\sigma_{T_0}$ keep unchanged. It's noted that the uncertainty of $T_0$ is usually about 30~40 ps$^1$, therefore it is an important timing error source at STCF.

To estimate the intrinsic timing uncertainty of DTOF, i.e.

$$\sigma_{DTOF} = \frac{\sigma_{\text{det}} \oplus \sigma_{\text{TTS}} \oplus \sigma_{\text{elec}}}{\sqrt{N_{\text{p.e.}}}}$$

we study the main contributing factors by considering a simple case. If a relativistic charged particle incident vertically into a thin Cherenkov radiator plate, a Cherenkov light cone will be produced. Assuming that the particle moves along the $z$-direction, the incident point is at the origin $(0,0,0)$, and the photon sensor is located at $(X, Y, 0)$, the distance from the incident point to the photon sensor is $D = \sqrt{X^2 + Y^2} = L \sin \theta_c$, where $L$ is the length of propagation (LOP) of Cherenkov photon and the $\theta_c$ is the Cherenkov radiation angle. The time of propagation (TOP) of a Cherenkov photon hit the photon sensor at $(X, Y, 0)$ is given by

$$\text{TOP} = \frac{Ln_g}{c} = \frac{Dn_g}{c \sin \theta_c} = \frac{n_p n_g \beta D}{c \sqrt{n_p^2 \beta^2 - 1}} = \frac{n_p n_g pD}{c \sqrt{n_p^2 p^2 - p^2 - m^2}}$$

where $n_p$, $n_g$ are the phase and group refractive index of fused silica, which are related to the wavelength $\lambda$, $c$ is the velocity of light in vacuum, and $\beta$, $p$ are the reduced velocity and momentum of the incident particle respectively. The excitation time of Cherenkov radiation can be deduced as $T_{det} = T - \text{TOP}$, if the time $T$ at the photon sensor is measured.

By differentiating the above equation, the sources of timing error emerge, as follow

$$\sigma_{DTOF}^2 = \sigma_T^2 + \left(\frac{\text{TOP}}{D}\right)^2 \sigma_D^2 + \left[\frac{\text{TOP} d(n_p n_g)}{n_p n_g D d\lambda} - \frac{\text{TOP}^3 c^2 d n_p}{n_p n_g^2 D^2 d\lambda}\right]^2 \sigma_\lambda^2$$

$$+ \left[\frac{\text{TOP}}{p} - \frac{\text{TOP}^3 c^2 (n_p^2 - 1)}{n_p^2 n_g^2 p D^2}\right]^2 \sigma_p^2$$

$^1$ A typical value for the T0 determination at the BESIII experiment.
including: $\sigma_T$ the single photo-electron (SPE) time resolution of the photon sensor and the electronics (also called $\sigma_{SPE}$), $\sigma_\lambda$ the chromatic dispersion effect, $\sigma_D$ the position resolution due to finite photon sensor size, and $\sigma_p$ the measurement error of particle momentum. To quantitatively estimate $\sigma_{DTOF}$, we assume a sensitive wavelength range of 300-650 nm for photon sensor and the dispersion effect would be $\sigma_\lambda \approx 75$ nm with a mean wavelength of 405 nm. The photon sensor along with the readout electronics contributes a timing uncertainty of $\sigma_{SPE} = 70ps$. The finite photon sensor pixel size of 5.5 mm gives a position error of $\sigma_D = 1.6mm$. The momentum error contribution is considered by a kaon of $p = 1$GeV/c. Furthermore, the thickness of fused silica plate (15 mm) also contributes an uncertainty to the excitation time of Cherenkov radiation, estimated as $\frac{\text{T} \text{hick}}{\beta c \sqrt{12}}$, and the multiple Coulomb scattering (MCS) effect causes an angular resolution, which is significant at low momentum (2.8 mrad for a kaon at 1GeV/c) and its impact to time uncertainty estimated as $\frac{\text{T} \text{OP}}{\tan \theta_c} \sigma_{\text{MCS}}$.

The calculation results for SPE are shown in Fig. 2, as a function of the photon transmission distance D. It can be seen that the timing jitter of photon sensor plays a major role when D is relatively short (< 1 m), while the dispersion effect gradually becomes the dominant factor when D is large (> 1.5 m), where proper optical design may be introduced to correct it if very precise timing is pursued, for instance the TORCH with a focusing component [17-18]. For DTOF detector, the typical D value is about 0.5-1 m, so the timing uncertainty from dispersion effect is smaller than the timing jitter of photon sensor, which means that compact DTOF design with no focusing component is acceptable. In addition, it can be seen that the spatial resolution, including thickness of fused silica and the pixel size of photon sensor, has little effect on the time uncertainty of DTOF. Therefore, a large pixel size photon sensor can be used to reduce the number of electronics readout channel. And the number of p.e. may increases with the thickness of radiator, and has little influence on time resolution of SPE, but it will bring more material budget.

![Fig. 2 The main DTOF timing error factors and their dependences on the distance from the particle (kaon @ p=1GeV/c) incident point to the photon detector.](image-url)
4. DTOF geometry optimization

Geometry optimization of the DTOF detector has been studied with Geant4 simulation (see section 5.1 for details). The π/K separation power of different geometry configurations are studied, which are obtained from a specific reconstruction algorithm (see section 5.2) and a likelihood method (see section 5.3). Some geometry configurations are listed in Table 1. We compare the DTOF performances with these different geometry configurations and study the effects coming from three main factors: radiator shape/size, radiator thickness and the setting of mirrors. The meaning of the letters in the table will be explained later.

Table 1. Description of the different DTOF geometry configurations

| Configuration/Geometry ID | 0   | 1   | 2   | 3   | 4   | 5   | 6   |
|--------------------------|-----|-----|-----|-----|-----|-----|-----|
| Radiator shapes (sector number) | 4   | 12  | 24  | 4   | 4   | 4   | 4   |
| Radiator thickness (mm)    | 15  | 15  | 15  | 10  | 20  | 15  | 15  |
| Outer side surface         | A   | A   | A   | A   | A   | M   | 45° M |
| Inner side surface         | A   | A   | A   | A   | A   | A   | A   |
| Lateral side surface       | M   | M   | M   | M   | M   | M   | M   |

4.1 Configurations

As shown in Fig. 3, we have studied three different radiator shapes (and sizes), corresponding to the Geometry 0, 1 and 2. The DTOF disc of Geometry 0 is made up of 4 quadrant sectors, in which the planar radiator is fan-shaped that can be viewed as a composite structure of 3 trapezoidal units, each ∼295 mm (inner side) /∼533 mm (outer side) wide, ∼470 mm high, and 15 mm thick. An array of 3×18 MCP-PMTs are optically coupled to the radiator along the outer side. The size of MCP-PMT is refer to R10754-07-M16 [20], which is a mature MCP-PMT produced by Hamamatsu. One MCP-PMT contains 4×4 anodes, each with a size of 5.5×5.5 mm². The disc of Geometry 1 is made up of 12 trapezoidal sectors, each with an area about one-third of Geometry 0. Each sector is readout by 18 MCP-PMTs. For Geometry 2 the disc is made up of 24 trapezoidal sectors, each coupled with 8 MCP-PMTs.

The effect of radiator thickness is studied by comparing Geometry 0, 3 and 4. The radiator thicknesses are 15 mm, 10 mm and 20 mm respectively. For all the geometry configurations listed in Table 1, their inner- and lateral-side surfaces of radiator are covered by absorber or reflective mirror, which we name “A” and “M” correspondingly. On the outer-side surface, a mirror can extend the acceptance of Cherenkov light, which increases the detected number of photons. As shown in Fig. 4, Geometry 5 has a mirror...
on its outer-side surface of radiator, which is equivalent to putting a mirror MCP-PMT parallel to the real one, and Geometry 6 places a mirror on the 45° chamfer, which is equivalent to putting a mirror MCP-PMT perpendicular to the real one. It is worth noticed that the addition of mirror MCP-PMT will increase the number of possible light path, which may affect the reconstruction and thus the time resolution.

Fig. 3 Three different radiator shapes. The disc of these configurations contains 4 (left), 12 (middle) and 24 (right) sectors, respectively.

Fig. 4 Three different configuration on outer surface of radiator. An absorber (left) or mirror (right) on outer surface, and a mirror on the 45° chamfer of outer side surface (right).

4.2 Comparison

Key results of the geometry optimization are listed in Table 2. The number of photo-electron is obtained from the Geant4 simulation (see section 5.1). For most geometry configurations except Geometry 5 and 6, better π/K separation power can be obtained with more p.e. number. The accumulated charge density on MCP-PMT anode is obtained from the background study (see section 6 for details), and the π/K separation power is obtained by a likelihood method (see section 5.3).

Table 2. Performance of different geometries at p=2GeV/c, θ = 24° and φ = 45°
| Performance/Geometry ID | 0   | 1   | 2   | 3   | 4   | 5   | 6   |
|------------------------|-----|-----|-----|-----|-----|-----|-----|
| Number of photoelectron for pions (except background) | 21.8 | 21.9 | 17.0 | 15.5 | 25.7 | 33.2 | 38.7 |
| Accumulated charge density on MCP-PMT anode (C/cm²) | 10.8 | 10.5 | 9.6 | 8.8 | 11.8 | 17.0 | 25.6 |
| π/K separation power | 4.17σ | 4.08σ | 3.66σ | 3.99σ | 4.27σ | 4.26σ | 4.19σ |

The effect of radiator shape/size is studied by comparing the DTOF performance with Geometry 0, 1 and 2. The numbers of p.e. of Geometry 0 and 1 are similar, and both significantly larger than Geometry 2. The main reason is that Geometry 2 has less MCP-PMTs per unit radiator area, because there is more death area between sectors. Also a small radiator will increase the light reflection times off the lateral-side mirror, causing more photon losses. As shown in Fig. 5, the different branches on the time-position hit pattern represent the light propagation from different paths, i.e. photons directly hit the MCP-PMT or reflected off the lateral-side mirror for 1, 2 or more times. In our simulation the maximum number of reflection by the lateral mirror of Geometry 0, 1 and 2 are 1, 2 and 4, respectively. Such reflection causes an overlap on the different hit branches, and increases the timing uncertainty. So Geometry 0 has the best π/K separation power of 4.17σ, while Geometry 2 has the worst of 3.66σ. Moreover, a large radiator can significantly reduce death area, indicating that Geometry 0 is a better choice.

Fig. 5 Time of the photoelectron arrival vs X channel ID for pions at p=2 GeV/c, θ = 24°, φ = 45°, for different geometries: geometry 0 (left), geometry 1 (middle) and geometry 2 (right)

Geometry 3 and 4 have different radiator thicknesses compared to Geometry 0. Although the number of photons generated in the radiator is proportional to its thickness, the p.e. yields of Geometry 3 and 4 are ~16 and ~26 respectively, which are not proportional to its thickness. The reason is that for different radiator thicknesses the number and size of MCP-PMTs are the same, which means a thicker radiator causes a larger probability of the light absorption by the outer-side absorber, or equivalently a
smaller photon acceptance. From the calculation results in section 3, the thickness of radiator has little effect on the time uncertainty of SPE, so more detected photons mean better time resolution. By comparison, we take the 15 mm thick radiator as the best choice, which keeps low impact of DTOF material budget on EMC while providing a performance redundancy to reduce the influence of detector aging effect in the long-term operation.

In order to increase the p.e. yield, a mirror is attached to the outer-side surface of radiator in different ways, as in Geometry 5 and 6. The number of p.e. received in these two geometries are ~33 and ~39, much higher than Geometry 0. However, as mentioned before, the outer-side mirror will also increase the number of possible light path, which causes “confusion” similar to the effect of multiple reflections off the lateral-side mirror, and degrades the time resolution. Therefore, even with more detected photons, the π/K separation powers of Geometry 5 and 6 are similar to Geometry 0. In additions, the accumulated charge densities of these two geometry configurations are much higher, which will affect the lifetime of MCP-PMT [21-22]. So we reject the options with mirror attached to the outer-side surface of the radiator.

By above comparison, an optimum geometry configuration of DTOF is obtained, i.e. Geometry 0, which is chosen as our baseline design. And more study results mentioned bellow are based on this geometry.

5. DTOF PID Performance

5.1 Geant4 Simulation

Geant4 [19] simulations are performed to study the expected performance of DTOF. A 20mm thick Aluminum plate is added 100mm before the DTOF detector, to simulate the material budget of the tracker endcap. Each DTOF sector is enclosed in a light-tight black box made of 5mm thick carbon fiber, occupying ~200 mm space along the beam direction. When tracking the Cherenkov photon propagation, the two lateral sides of radiator are set reflective with a reflection factor of ~ 92%. The surface roughness of the radiator is simulated by randomizing the normal direction of the facet by σ = 0.1° (corresponding to an average reflection factor of ~ 97%). The windows of photon detector are directly coupled to the surface of the fused silica with no any other pads, and a quantum efficiency varying with the wavelength is given to simulate the response of the photon detector (refer to Hamamatsu R10754-07-M16, [20]). Pions and kaons are emitted from the interaction point at different momenta and directions. A typical Cherenkov photon hit pattern is displayed as in Fig. 6 by pions at p=2 GeV/c, θ = 24° and φ = 15°. A clear correlation between time and the hit position (sensor pixel) is demonstrated. Two bands, one for direct photons and another for indirect photons with one reflection off the lateral side, are well separated except for a few sensors close to the side. The mean number of photons detected by the MCP-PMT arrays is ~21, also shown in Fig. 7. To further study the time resolution of DTOF detector, a reconstruction algorithm is required, as shown below.
5.2 Reconstruction algorithm

The DTOF reconstruction is performed in the coordinate system shown in Fig. 7, for one DTOF quadrant. According to the Cherenkov angle relation $cos(\vec{\theta}_c) = \frac{1}{n_p(\beta)} = \frac{\vec{u}_t \cdot \vec{u}_p}{|\vec{u}_t||\vec{u}_p|}$, where $\vec{u}_t = (a, b, c)$ is the velocity vector of incident particle when impinging the radiator, $\vec{u}_p$ is the velocity vector of emitted Cherenkov photon, $n_p$ is the refractive index of the radiator and $\beta$ is the reduced speed of the particle (set a hypothetical particle to calculate $\beta$). The directional components of $\vec{u}_p$ can be expressed as $(\Delta X, \Delta Y, \Delta Z)$, representing the 3D spatial difference between the photon sensor pixel and the incident position on the radiator surface, as depicted in Fig. 7 (right). Although the 2D (X and Y) difference can be readily obtained, $\Delta Z$ must be deduced with a certain particle species hypothesis. If $V = cos(\vec{\theta}_c)$ is known, the equation about $\Delta Z$ can be found as

$$(c^2 - V^2)\Delta Z^2 + 2c(a\Delta X + b\Delta Y)\Delta Z + (a\Delta X + b\Delta Y)^2 - V^2(\Delta X^2 + \Delta Y^2) = 0$$

By solving this equation we find $\Delta Z = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$, with $A = c^2 - V^2$, $B = 2c(a\Delta X + b\Delta Y)$ and $C = (a\Delta X + b\Delta Y)^2 - V^2(\Delta X^2 + \Delta Y^2)$. In order to get a real solution, $\Delta = B^2 - 4AC \geq 0$ is required. After some further physical cuts $V > 0$ (Cherenkov photon forwardly emitted) and $\frac{\Delta X^2 + \Delta Y^2 + \Delta Z^2}{\Delta Y^2} \geq \frac{1}{n_p^2}$ (ensuring internal total reflection) are applied, the minimal solution ($\Delta Z = \min(|\Delta Z_1|, |\Delta Z_2|)$) is taken as the optimum solution.

The LOP of photon inside the radiator is obtained by $LOP = \Delta Y \frac{\sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2}}{|\Delta Y|}$. The precision of the reconstructed LOP is $\sim 3.3$mm, for pions at $p=2$GeV/c, $\theta = 24^\circ$ and $\phi = 45^\circ$, shown in Fig. 8. Furthermore, we find the reconstruction algorithm works well for most photon sensors, no matter the incident position of particles.
Fig. 7 The coordinate system used in DTOF reconstruction (left) and the direction of Cherenkov photon, the green line represents Cherenkov photon while the pink line represents incident charged particle.

Fig. 8 The reconstructed propagation length of Cherenkov photons (left) and its uncertainty (right) in the fused silica plate of DTOF.

By applying formula $\text{TOF} = T - \text{TOP} - T_0 = T - \frac{L \pi \theta}{c} - T_0$, the TOF information is obtained. As mentioned above, the light may have different path to the same pixel sensor. So the TOFs of all the possibly paths are reconstructed, and retain the one closest to the hypothetical value. Fig. 9 shows the time resolution of the DTOF detector by pions at $p=2\text{GeV/c}$, $\theta = 24^\circ$ and $\varphi = 45^\circ$, for the SPE and the average of all photons, respectively. The timing jitter of MCP-PMT and electronics are not taken into account. For the SPE, the intrinsic time resolution from DTOF reconstruction is $\sim 41\text{ ps}$, while by averaging the timing information over all ($\sim 20$) detected photons the timing jitter shrinks to $\sim 11\text{ ps}$. To verify these reconstruction results, we apply a TOP-position calibration, where the average LOP collected by each sensor pixel and the average velocity of Cherenkov photons are used to calculate the TOP, and the same results are obtained from simulation truth, with no further correction (such as the dispersion effect). It’s noted that in the TOF distribution plot, a low (but visible) long tail shows on both sides of the main peak. The tail is mainly caused by secondary particles along with the primary pion, mostly $\delta$-electrons.
5.3 PID capability

With a certain particle species hypothesis, the TOF measurement is given by

$$TOF_h = T - TOP_h - T_0 = TOF_t + TOP_t - TOP_h$$

where \( t \) and \( h \) denote truth particle and different hypothesis particle, respectively. Then the expectations of each hypothesis particle are compared to study the PID capability of DTOF. Fig. 10 shows the reconstructed TOF distributions of both pions and kaons at 2GeV/c, for the SPE and the average of all photons when convoluting all contributing factors. One can easily find if the particle hypothesis is correct, the reconstructed TOF peak is at its right position, with a resolution of \( \sim 50 \) ps, as in Fig. 10 (right). However, if the hypothesis is not true, the reconstructed TOF peak is shifted with respect to its expectation, mainly due to the TOP reconstruction deviation. This shift makes the separation between pion and kaon TOF peaks even larger, which may benefit the PID power. By directly comparing the TOF information, a \( \sim 3\sigma \) separation power for \( \pi/K \) at 2GeV/c is achieved, fulfilling the required PID capability of DTOF. Furthermore, the separation power gets stronger if we compare the reconstructed TOFs of various hypotheses for the same set of particles. For either pion or kaon samples at 2GeV/c, the separation power reaches \( \sim 4\sigma \) by comparing the TOF distributions under \( \pi \) or \( K \) hypotheses.

To further evaluate the PID capability of DTOF, we apply the likelihood method. The
likelihood function is constructed by

\[
\mathcal{L}_h = \prod_{i=1}^{n} f_h(TOF_i^h), \Delta \ell = \log \mathcal{L}_\pi - \log \mathcal{L}_K
\]

where \( h \) denotes hadron species (in our case \( \pi \) and K) and \( i \) accounts for each detected photon. The probability density function \( f_h \) is taken as the Gaussian fit to the expected TOF distribution (as in Fig. 10 (left)) after normalization, plus a constant background of 0.05. Shown in Fig. 11 are the reconstructed \( \Delta \ell \) for 2GeV/c \( \pi \) and K emitted at different angles. Despite the very different particle directions, the separation power of DTOF are similar, reaches \( \sim 4\sigma \) or better all over the DTOF sensitive area, shown in Fig. 12 (left). The \( \pi/K \) separation power at different momenta is also shown in Fig. 12, which indicate a better performance of DTOF at low momentum.

Fig. 11 The likelihood PID capability of the DTOF detector for \( \pi/K \) separation at 2 GeV/c, emitted at different angles.

Fig. 12 \( \pi/K \) separation power: \( p = 2\) GeV/c at different directions (left) and \( \phi = 45^\circ \) at different momenta (right).

6. Background impact

In the experiments of high luminosity machine such as STCF, the intensive background has significant impact on the performance of various detectors. The background sample particles obtained from specific machine-detector interface (MDI) study [23] are used as input to the Geant4 simulation of DTOF, to estimate the effect of background on the DTOF performance. The background particles hitting DTOF are mainly gamma
photons, electrons and a few hadrons, for which the hit rate of all particles on DTOF is about $7 \times 10^9$ Hz. The energies of most backgrounds are smaller than the Cherenkov threshold, only a part of charged particles or some secondary particles produced in DTOF radiator will generate Cherenkov light. These backgrounds include two main parts: the beam-induced background ($\sim$75%) and the physical background ($\sim$25%). The beam-induced background is uniformly distributed in time, which is not related to the beam bunch crossing, while the physical background is related to the collisions during bunch crossing (once per 8 ns), exhibiting characteristic time structure. Combining these two kinds of background time structures, the overall time distribution of background hit on DTOF can be obtained, as shown in Fig. 13.

![Fig. 13 Overall time distribution of background electrons and gamma photons on DTOF.](image)

In the Geant4 simulation, the hit position, direction and energy of the background particles are extracted from the background samples. The time window of the signal acquisition is 100 ns, within the interval [-40 ns, 60 ns] so that the real signal is in the middle of the time window. In this time window, the number of background particles is given by Poisson distribution. The hit time is sampled from a uniform distribution rather than the specific distribution shown in Fig. 13. This is because we find the different time distribution has little effect on the results, and a uniformity distribution can significantly simplify the sampling process.

Pions and kaons are generated in the Geant4 simulation along with the background samples to study the effect of the background. The background may increase the number of photoelectrons detected by DTOF in a single event, resulting in an increased possibility of multiple hits in a single channel. The correction of multiple hits in data processing is applied, which means that in the time window of [-40 ns, 60 ns], when a single channel contains multiple hits, only the earliest photoelectron signal is taken and all other hits are dismissed. The average number of photoelectrons for a pion at $p =$
2GeV/c is about 33 when taking the background hits (about 11 in 100 ns window) into account and applying the correction of multiple hits in single channel. It’s noted that if the average number of background photoelectrons is 11 for a time window of 100 ns, and assuming an MCP-PMT gain of $10^6$, the average accumulated charge density on the MCP-PMT anode is about $11C/cm^2$ over 10-year STCF operation (50% run time), which indicates that the aging of the photocathode, i.e. the loss of quantum efficiency due to ion backflow, poses a challenge to the lifetime of MCP-PMT [21-22]. Moreover, a new MDI with more shielding can further suppress the background and extend the lifetime of MCP-PMT in the future.

Fig. 14 2-D time-position map of DTOF (left) and the TOF distribution of single photo-electron signal (right), both with background hits.

Shown in Fig. 14 (left) is the 2-D time-position map of DTOF hits, by pions at p=2 GeV/c, $\theta = 24^\circ$ and $\phi = 45^\circ$. It can be seen that hits by background particles are uniformly distributed throughout the phase space, while the real signal hits are concentrated as a band. After time reconstruction, the TOF distribution of the SPE signal can be obtained, as shown in Fig. 14 (right). The reconstructed TOF of the real signal in the figure shows a Gaussian distribution (mean 5.22 ns, sigma ~96 ps, with the convolution of all contributing factors), while the TOF of background particles are distributed rather uniformly. Some SPEs do not meet the reconstruction conditions and are taken as background during the reconstruction process, shown as the peak with zero TOF in the figure. Due to the uniform distribution of the reconstructed background signal, the influence of the background can be largely eliminated by using the maximum likelihood method. The $\pi/K$ resolution is found to be 4.15$\sigma$, as shown in Fig. 15. Moreover, considering the Poisson fluctuation of background count, even with an extreme condition of 3 standard deviation above the average background level, the $\pi/K$ resolution remains at 4.12$\sigma$. This PID performance still meeting the requirement of 3$\sigma$ $\pi/K$ separation for the DTOF, i.e. the background effect on $\pi/K$ identification is fairly small.
7. Conclusion

A conceptual design of the DTOF detector is proposed as the endcap PID detector for the experiment at STCF to provide an effective π/K/p identification. The main sources contributing to the timing uncertainty of the DTOF detector are analyzed. It’s shown that for short photon propagation length the timing uncertainty of photon sensor contributes most to the intrinsic time resolution, while the dispersion effect gradually becomes the dominant factor when the transmission distance of photon is large. By comparison, an optimum quadrantal radiator, which has a thickness of 15 mm and was attached an absorber on its outer side surface, is chosen as our baseline design. The performance of DTOF is studied with a Geant4 simulation and the reconstruction algorithm of DTOF is developed. The Geant4 simulation indicates an overall reconstructed TOF time resolution of ∼50ps with an average of ~20 photons detected by the MCP-PMT arrays when convoluting all contributing factors. It’s worth noting that the uncertainty of T0 dominates the overall timing error, so an optimal design of STCF bunch size is crucial. By applying the likelihood method, a π/K separation power of DTOF of ∼4σ or better at the momentum of 2 GeV/c is achieved over the full DTOF sensitive area, fulfilling the physics requirement for the PID detector at STCF. Furthermore, the background effect on π/K identification of DTOF detector is fairly small, while the average accumulated charge density on the MCP-PMT anode is about 11C/cm² over 10-year STCF operation, which poses a challenge to the lifetime of MCP-PMT.

Acknowledgments

This work was supported by the Chinese Academy of Sciences [Grant NO.: GJJSTD20200008]; the National Natural Science Foundation of China [Grant No. U1932202, 11775217]; the Double First-Class university project foundation of USTC. The authors thank Hefei Comprehensive National Science Center for their strong support.

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