Time calibration for barrel TOF system of BESIII

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Abstract. The time calibration for barrel TOF system of BESIII is studied in this paper. The time resolution for single layer and double layer have been achieved about 97 ps and 78 ps for electrons in Bhabha events respectively. The pulse height correction using electronic scan curve and the predicted time calculated using Kalman filter method are introduced. This paper also describes the analysis of correlation of measured time.

1. Introduction
The Beijing electron-positron collider BEPCII [1], is a double-ring multi-bunch collider with a design luminosity of about $1 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ optimized at a center-of-mass energy of $2 \times 1.89\text{GeV}$, roughly 100 times higher than the luminosity of BEPC. Its detector, the Beijing Spectrometer (BESIII) [2] is a high precision general purpose detector which is designed for the high luminosity at $\tau$-charm energy region. Particle identification (PID) plays an essential role in the experimental study of $\tau$-charm physics. The time-of-flight (TOF) detector systems based on plastic scintillation counters have been very powerful tools for particle identification in collider detectors. Its capability of PID is determined by the flight time difference of particles of different species and the time resolution of detector. This paper describes the scheme of time calibration for the barrel TOF using Bhabha events acquired on BESIII.

2. TOF system in the BESIII detector
The BESIII detector consists of a beryllium beam pipe, a helium-based small-cell multilayer drift chamber (MDC), a time-of-flight (TOF) system, a CsI(Tl) crystal calorimeter (EMC), a superconducting solenoidal magnet with the field of 1 T, and a muon identifier (MU) of resistive plate counters (RPC) interleaved with the magnet yoke plates. The physics program of the BESIII experiment covers studies of the production and decay properties of charmonium states, light hadron spectroscopy and decay properties, charm physics, including the decay properties of $D$ and $D_S$ and charmed baryons, $\tau$-physics and search for new physics etc.

The cross-sectional view of the TOF system inside the CsI crystal calorimeter is shown in Fig.1. The time-of-flight system is based on plastic scintillator bars read out by fine mesh photomultiplier tubes (PMT) directly attached to the two end faces of the bars. It consists of a barrel and two end caps. The barrel TOF consists of two layers of 88 plastic scintillator elements arranged in a cylinder of the mean radius of about 81 cm, which is mounted on the outer surface of the carbon fiber composite shell of the MDC. The two single layer end caps, each with 48 trapezoidal shaped scintillation counters, are located outside the MDC end caps. The scintillator is 5 cm thick and 48 cm long. Each counter is read out from one end of the scintillator by a
Figure 1. Schematic drawing of TOF on BESIII

single fine mesh PMT. The solid angle coverage of the barrel TOF is $|\cos\theta| < 0.83$, while that of the end cap is $0.85 < |\cos\theta| < 0.95$. TOF counters also play a critical role as fast triggers for charged particles.

The factors contributing to time resolution and estimated magnitudes are summarized in Table 1.

| Item                                      | Barrel time resolution | End cap time resolution |
|-------------------------------------------|------------------------|-------------------------|
| Intrinsic time resolution of one TOF layer for 1 GeV muon | 80~90 ps               | 80 ps                   |
| Uncertainty from bunch length             | 15mm, 35 ps            | 15mm, 35 ps             |
| Uncertainty from bunch time              | ~20 ps                 | ~20 ps                  |
| Uncertainty from z/r position            | 5 mm, 25 ps            | 10 mm, 50 ps            |
| Uncertainty from electronics             | 25 ps                  | 25 ps                   |
| Resolution of expected time of flight    | 30 ps                  | 30 ps                   |
| Time walk                                 | 10 ps                  | 10 ps                   |
| Total time resolution, one layer of TOF for 1 GeV muon | 100~110 ps             | 110~120 ps              |
| Total time resolution, double layer of TOF for 1 GeV muon | 80~90 ps               |                         |

The target of the time resolution of one layer and double layer of barrel TOF are about 100 ~ 110 ps and 80 ~ 90 ps respectively, the time resolution of end cap TOF is about 110 ~ 120 ps.
3. Time calibration for barrel TOF

3.1. TOF raw data

In the case of beam collision events, BEPCII will be operated in the two-ring and multi-bunch colliding mode, bunches with spacing of 8 ns will be filled in each storage ring. The time measurement system of TOF adopts CERN HPTDC (High Performance Time to Digital Converter) chip. The trigger cycle is 24 ns, which equals the duration of 3 bunches. When two bunches collide and generate a good event, the raw measured time $TDC$ recorded by electronics is the time interval of the start time to the arrival time of detector’s hit signal. This time interval may differ from which is between the collision and the arrival time of the hit signal in the detector. The interval of the trigger start time to the real collision time, is described as event start time $t_0$[3]. The measured time of flight from the collision to the arrival time is expressed as $t_{\text{raw}}$:

$$t_{\text{raw}} = TDC - t_0.$$  \hfill (1)

The charge-to-time converter circuit in FEE module transforms the pulse’s charge information of the signal to the time interval, which is measured by HPTDC[4][5]. The hit position along the direction of scintillator ($z$ for barrel and $r$ for end cap) of each track is reconstructed using the MDC track trajectory extrapolation[6]. Fig.2 (a) shows the raw measured time $t_{\text{raw}}$, (b) shows corresponding pulse height distributions respectively, the raw measured time versus $z$ hit position of charged track distribution is shown as (c) and (d) is the pulse height versus $z$ hit position. The electrons in Bhabha events are used for these plots.

3.2. The pulse height correction

There is an bump close to high boundary in the distribution of raw measured pulse height, which is caused by the electronics saturation. The pulse height distribution is adequately described by the highly-skewed Landau distribution for plastic scintillator bars. The long Landau "tail" extends beyond the dynamic range of TOF electronics readout system.
3.3. The predicted time

A track fitting algorithm based on the Kalman filter method has been employed for MDC reconstruction[7]. The Kalman filter method updates the fitting results in each step with the addition of measurement points, then it deals with multiple scattering, energy loss and non-uniformity of magnetic field as a deviation with a Gaussian distribution in each step, to yield more accurate track parameters and error matrix. The accurate predicted time $t^i_{\text{pred}}$ calculated using Kalman filter method is expressed as:

$$t^i_{\text{pred}} = \sum_{\text{step}} t^i_{\text{step}} + t^i_{\text{TOF}},$$

(3)

where $i$ is the desired particle hypothesis ($e$, $\mu$, $\pi$, $K$, $p$), $L_{\text{step}}$ is the corresponding path of flight of this step, $c$ is the velocity of light in vacuum, the flight velocity of charged particle in this step $\beta_{\text{step}} = p/\sqrt{p^2 + m_i^2}$, $p$ is the measured momentum using Kalman filter algorithm in this step and $m_i$ is the mass of the particle $i$. The predicted time outside MDC could be calculated using similar formula. The predicted time obtained using Kalman filter method is more accurate than the one calculated with the assumption that the track trajectory moving in the detector is described as a standard helix.

4. The time calibration

The calibration of TOF is proceeded by comparing the measured time $t_{\text{mea}} = t_{\text{raw}} - t_{\text{cor}}$ against the predicted time $t_{\text{pred}}$,

$$\Delta t = t_{\text{mea}} - t_{\text{pred}},$$

(5)
where $t_{\text{cor}}$ is the correction term. The correction term $t_{\text{cor}}$ is a function of pulse height $Q$ and hit position $z$, for barrel TOF, we take the following 7-term empirical form:
\[
t_{\text{cor}} = P_0 + \frac{P_1}{\sqrt{Q}} + \frac{P_3}{Q} + P_4 \cdot z + P_5 \cdot z^2 + P_6 \cdot z^3,
\] (6)
where $P_i (i=0,1,...,6)$ are the calibration constants: $P_0$ represents the delay time, such as cabling, etc.; the correction function of time walk effect is represented by the term containing $P_1$; $P_2$ and $P_3$ are used to describe the saturation of electronics, etc.; a polynomial containing $P_4$ and $P_6$ describes the correction to the effective velocity of light in the scintillator.

A $\chi^2$ minimization method is applied by defining a set of
\[
\chi^2(\text{readout unit}) = \sum_{\text{event}} (t_{\text{mea}} - t_{\text{pred}})^2
\] (7)
in each readout unit independently. The calibration constants, $P_0$ to $P_6$, are obtained from offline data, electrons in Bhabha events, by setting the derivative of Eq.7 with respect to $P_i$ to zero.

5. Analysis of correlation of measured time[8]
We do not expect to get the full benefit of the statistical factor $1/\sqrt{2}$ for the system time resolution compared to a single layer counter system in the double layer, since the distinctive measurements of time correlate due to the common event start time. A covariance matrix $V_t$ is defined with its terms are given by $(V_t)_{ij} = < \delta t_i \delta t_j >$, where $\delta t_i = t_i - \bar{t}$, $\bar{t}$ is the average of $t_i$. The best linear estimator for the TOF which accounts for all measurements, including errors and correlations can be constructed generally as
\[
\bar{t} = \sum_i w_i t_i, \quad \sum_i w_i = 1,
\] (8)
where $w_i$ is the weight. Using the standard deviation, we get
\[
\sigma_t^2 = \sum_{ij} w_i w_j (V_t)_{ij}
\] (9)
In order to minimize $\sigma_t^2$ subject to the condition $\sum_i w_i = 1$, the Lagrange multiplier technique is applied,
\[
\sigma_t^2 = \sum_{ij} w_i w_j (V_t)_{ij} + \lambda (\sum_i w_i - 1)
\] (10)
and set the derivative of Eq.10 with respect to the $w_i$, and Lagrange multiplier $\lambda$ to zero. This give the solution

$$w_i = \frac{\sum_k (V^{-1})_{ik}}{\sum_j (V^{-1})_{jk}}$$

(11)

For a given double layer barrel TOF system, the measured time could be decomposed as

$$t_1 = t_c + (t_D)_1, \quad t_2 = t_c + (t_D)_2,$$

(12)

where $t_1$ and $t_2$ represent the measured time of a single end readout or the weighted average measured time of a single layer, $t_c$ represents the common part of time between the two measurements, $(t_D)_1$ and $(t_D)_2$ represent the uncorrelated part of the measurements. The covariance matrix for $t_1$ and $t_2$ can be expressed as

$$V_t = \begin{pmatrix} \sigma_1^2 & \sigma_c^2 \\ \sigma_c^2 & \sigma_2^2 \end{pmatrix}$$

(13)

where $\sigma_1$ and $\sigma_2$ are the time resolution of measured time $t_1$ and $t_2$, $\sigma_c$ is the fluctuation of $t_c$. Substituting the special expression of Eq.13 into Eqs.8 to 11, the weights could be expressed as

$$w_1 = \frac{\sigma_2^2 - \sigma_c^2}{\sigma_1^2 + \sigma_2^2 - 2\sigma_c^2}, \quad w_2 = \frac{\sigma_1^2 - \sigma_c^2}{\sigma_1^2 + \sigma_2^2 - 2\sigma_c^2},$$

(14)

Fig.4 shows $\Delta t$ distributions for single end readout unit, for the weighted average time of a single layer and for double layer. The time resolutions for the weighted average time of a single layer and for double layer are found to be about 97 ps and 78 ps respectively. The time resolutions versus $z$ hit position distributions for east and west end readout units and for a single layer and double layer are shown in Fig.5.

**Figure 5.** Time resolution versus $z$ hit position distributions for east and west end readout unit, a single layer and double layer.
6. Summary
The capability of particle identification by the TOF detector requires a good time resolution. In this paper, the calibration for the barrel TOF of BESIII is presented. The time resolutions for single layer and double layer are found to be about 97 ps and 78 ps for electrons in Bhabha events respectively, which have achieved the designed goal. The electronics scan curve of each electronics channel is obtained to correct the measured pulse height values which are beyond the dynamic range. The Kalman filter method is employed to calculate the predicted time instead of taking the track trajectory as a standard helix. The correlations analysis of TOF measured time is also included in this paper.

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