Determination of event start time at BESⅢ *

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Abstract The principle of the method for the BESⅢ event start time determination and the code construction are described. The investigation of influence of the noise, the method of rejecting noise and the performance checking by the Monte Carlo physics data sample are also presented. The preliminary results got from the Monte Carlo simulation are presented, the reconstruction efficiency of $J/\psi \to$ anything events at noise level $0\sim60\%$ can achieve above 99%, and the error rate is below 1%.

Key words event start time, time-of-flight, drift-chamber, track reconstruction

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1 Introduction

The BESⅢ detector[1] to be worked at the Beijing Electron-Positron Collider (BEPCⅡ)[2] consists of the beryllium beam pipe, the Main Drift Chamber(MDC), the Time-Of-Flight(TOF)counters, the Electromagnetic Calorimeter(EMC) and a Muon Identifier(MUID).

BEPCⅡ, designed to reach a luminosity of 10^{33} cm$^{-2}\cdot$s^{-1} at c.m. energy of 3.89 GeV, an im-

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provement of a factor of 100 with respect to BEPC, will be operated in the two-ring and multi-bunch colliding mode, 93 bunches with the bunch spacing of 8 ns will be filled in each storage ring. The time measurement system of MDC adopts CERN HPTDC (High Performance TDC) chip, and uses "the pipeline arrangement method"[3]. The trigger cycle is 24 ns, which equals the duration of 3 bunches. When two bunches collide and generate a good event as shown in Fig. 1, according to the logic of the trigger system and the MDC time measurement system, the event time TDC got from MDC or TOF is the time interval of the trigger start time to the arrival time of Detector's hit signal. This time interval may differ from the time interval between the collision and the arrival time of the hit signal in the detector, depending on the event is created at which bunch in three bunches during this trigger cycle, these two timing may differ by 0 ns, 8 ns or 16 ns. The interval of the trigger start time to the real collision time, described as event start time(T_{EST}), can not be uniquely determined by online system and have to be calculated by offline data analysis.

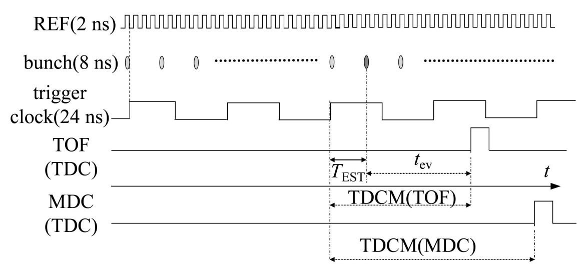

Fig. 1. The BESIII time system.

2 The principle of event start time

2.1 The algorithm to calculate the event start time

From Fig. 1, we can get the equation to calculate the T_{EST} (in the TOF case):

$$T_{\mathrm{EST}} = TDCM - T_{\mathrm{ev}} \ . \quad (1)$$

T_{EST}: event start time, the interval of the trigger start time to the real collision time; $TDCM$: Time measured by detector electronics system for a hit signal; T_{ev}: The time interval from collision time to the arrival time of the hit signal.

From Eq. (1), there are two main tasks to calculate T_{EST}: 1) assignment of the detector to find a usable $TDCM$. 2) calculating T_{ev}. In the situation of the BESIII detector geometry and time measurement system, the TOF and MDC detectors can be used to calculate the T_{ev}. The best choice is TOF, since it is near MDC and has the highest time measurement precision, and the second choice is MDC. The T_{ev} includes the particle flight time and the signal transform time in the detector. To get the particle flight time we must know the particle flight length, so a fast MDC track reconstruction[4] is needed. Also, considering the different flight time due to different kinds of particles, particle identification is needed. So a framework of the event-start-time algorithm is designed as shown in Fig. 2.

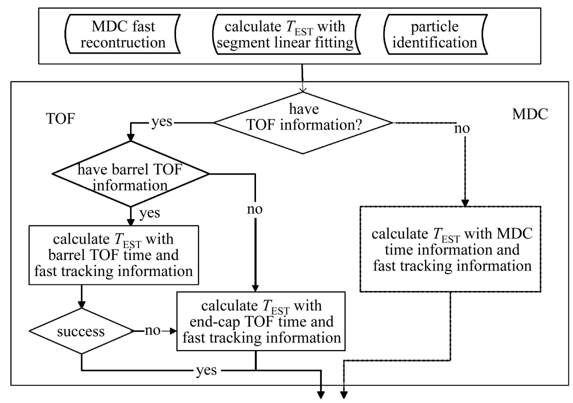

Fig. 2. The event start time programme flow.

After the MDC fast track reconstruction and particle identification, T_{EST} will be calculated by TOF and MDC separately. If there is TOF information, it can be used to calculate T_{EST}, otherwise, the MDC information will be used to determine T_{EST}.

2.2 MDC fast track reconstruction and particle identification

To get the flight length of the charged particles, the MDC fast track reconstruction (fast tracking) is performed, which includes six parts: the data unpacking, the segment finding in each super-layer, the $r-\phi$ segment linking, the $r-\phi$ track fitting, the stereo segment linking, and the s-z track fitting[5]. In order to get the precise flight time, we have to do particle identification. The concrete methods are: 1) to extrapolate the track from the MDC detector to the EMC detector, and match with the EMC cluster, then calculate the ratio of the energy deposition in the EMC and the charged track momentum: E/p. If E/p is within certain window, the track is identified as $e^{+/-}$; 2) p or $\bar{p}$ is identified by track's $\mathrm{d}E/\mathrm{d}x$ information. The other particles are considered as pions.

2.3 To calculate event start time by TOF

The TOF detector consists of the barrel and end cap parts, placed out-side the MDC. The algorithm is designed by two steps based on the TOF geometry.

At first, the barrel TOF hit, which is associated with an MDC track, is selected to calculate the T_{est}[6]. t_{ev} can be calculated by the following equation:

$$t_{\mathrm{ev}} = t_{\mathrm{tof}} + t_{\mathrm{pro}} + t_{\mathrm{PMT}} + t_{\mathrm{elc}} \ , \quad (2)$$

$t_{\rm tof}$: the time of flight of charged particle

$$t_{\rm tof}=\frac{s}{c}\cdot\sqrt{\frac{m^2}{p^2}+1}\ ,$$

s: the length of the MDC track extrapolated to the TOF inner radius; c: the velocity of light; m, p: the particle mass and momentum, the particle type is determined in 2.2. $t_{\rm pro}$: the light propagation time in the TOF counter

$$t_{\rm pro}=Z_{\rm TOF}/\upsilon\ ,$$

υ: the velocity of light in the scintillator; $Z_{\rm TOF}$: z value of TOF hit. $t_{\rm PMT}$: the transit time of PMT, treated as a constant. $t_{\rm elc}$: the delay-time of electronic signal, treated as a constant.

If no good TOF hit is found in the barrel counters, the end-cap TOF counter will be tried. $T_{\rm est}$ will be calculated by the east end cap or the west end cap according to the track's direction. The principle of the calculation is almost the same as that in the barrel part, but the method is more complex compared with that of the barrel part due to the end cap TOF geometry[1]. Finally the event start time $T_{\rm est}$ is obtained by averaging all the $T_{\rm est}$ got from the hits in an event.

2.4 To calculate event start time by MDC

The $T_{\rm est}$ has to be calculated by MDC information if no TOF information can be used. The $T_{\rm ev}$ can be calculated by the following equation:

$$t_{\rm ev}=t_{\rm f}+t_{\rm drift}+t_{\rm wp}+t_{\rm elc}\ , \tag{3}$$

$t_{\rm f}$: the flight time of the particle from the collision point to the hit cell. $t_{\rm drift}$: the drift time of electrons. $t_{\rm wp}$: the signal propagation time in the wire. $t_{\rm elc}$: the delay-time of electronics, treated as a constant.

MDC consists of 19 axial layers, 24 stereo layers and 6796 small drift cells[7]. As the geometry of stereo layers is more complex than the axial layers, the time $t_{\rm f}$, $t_{\rm drift}$ and $t_{\rm wp}$ have to be calculated by two methods for the axial and stereo layers, respectively. Finally, the event $T_{\rm est}$ is calculated by averaging all of the hit cell's $T_{\rm est}$ in an event.

2.5 To calculate event start time by segment linear fitting

The "segment linear fitting method"[8] is used to calculate $T_{\rm est}$ if the above two different ways in Section 2.3 and 2.4 fail because none of tracks is found by the MDC fast track reconstruction algorithm, while the "hitted" segments could be found in the super-layer of MDC. As we know that there could be 4 hits in a hitted segment and the event start time is an additional constant included in each hit information(TDC). The event start time then can be extracted from the segment by fitting the 4 hits with a straight line, as illustrated in Fig. 3.

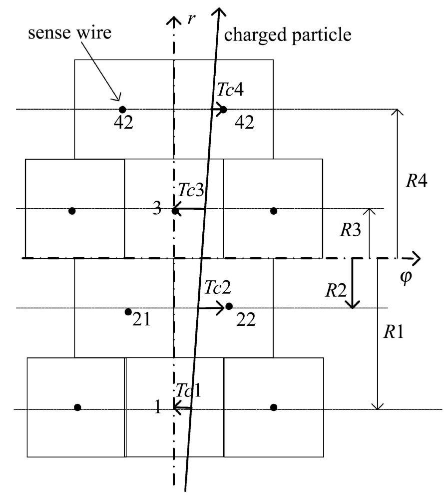

Fig. 3. The event start time calculated by segment linear fit.

In order to reject the noise and unqualified segments, good segments are selected: no hits in adjacent cells in the same layer for a hit cell; 4 hits in successive layers of any super-layer. Finally, only the zig-zag pattern segment as shown in Fig. 3 is used for a straight line fit by the following equation:

$$\begin{cases} Tc1-t0c & =R1\times Pa+Pb \\ T2-(Tc2-t0c) & =R2\times Pa+Pb \\ Tc3-t0c & =R3\times Pa+Pb \\ T4-(Tc4-t0c) & =R4\times Pa+Pb \end{cases} \tag{4}$$

In Eq. (4), $Tc1, Tc2, Tc3$, and $Tc4$ are the TDC time of 4 hits, $T2$ and $T4$ are the drift time of ionized electron corresponding to half cell widths along ϕ direction. $R1, R2, R3$, and $R4$ are the distance between the sense wire of cells and the center of segments along r direction. Pa and Pb are the slope and intercept of the straight line, and Pa is deduced from the geometrical relation as follows:

$$Pa=\frac{(R3-R1)\times(Tc3-Tc1)}{(R3-R1)^2+(R4-R2)^2}+\frac{(R4-R2)\times(T4-T2-Tc4+Tc2)}{(R3-R1)^2+(R4-R2)^2}\ .$$

The event start time $t0c$ is calculated by Eq. (5) and the optimizing function χ^2 is defined as the following equation:

$$t0c=[Tc1+Tc2+Tc3+Tc4-(T2+T4)+(R2+R4-R1-R3)\times Pa]/4, \tag{5}$$

$$\chi^2=(Tc1-t0c-R1\times Pa-Pb)^2+(T2-Tc2+t0c-R2\times Pa-Pb)^2+(Tc3-t0c-R3\times Pa-Pb)^2+(R4-Tc4+t0c-R4\times Pa-Pb)^2.$$

Finally, the event start time is got by averaging all the $t0c$ obtained from the good segments in an event.

2.6 Cosmic event

In the case of the cosmic events, the particle track is normally regarded as two track segments, namely incoming and outgoing. This label is decided either by comparing the azimuthal angle of the two TOF hits or their TDC difference. If there are multi-hits (>2) on the TOF counters, two well separated hits (in ϕ) with the maximum charge deposit are picked for event start time determination. Event start time determination method for beam collision and cosmic events differ mainly in terms of the sign of $t_{\rm tof}$ (as defined in Eq. (2)). In the collision events $t_{\rm tof}$ for all hits have the same sign while in the cosmic events two legs(assumed as μ) have opposite sign.

3 Preliminary results

In order to check the correctness and robustness of the algorithm and optimize the parameters of the code, the e, μ single-track events with momentum of 1 GeV/c and multi-track events (J/ψ → anything) are generated by Monte Carlo[9]. The event start time is set at 0, 8 ns, 16 ns randomly. For the MDC detector, 122 μm is assumed as the average spatial resolution, the dip angle $\cos\theta$ is set from −0.93 to 0.93 and the average wire efficiency is assumed to be 98%. The 85 ps intrinsic time resolution is set for the TOF barrel part and 80 ps for the end-cap parts.

The preliminary results of $T_{\rm est}$ calculated by TOF, MDC and segment fitting are shown in Fig. 4 for μ track (x-coordinate is the event start time, in a unit of ns, and y-coordinate is the entries of events). The reconstruction efficiency, defined as the entries of events which start time can be given by the algorithm divided by the total entries of events, is 99.98% , in which 88.14% by TOF as shown in Fig. 4(a), 11.84% by MDC shown in Fig. 4(b). Others are calculated by the segment fitting method. From Fig. 4 we can see the events from different bunches separate clearly, and the time resolution by the TOF, MDC method is ∼0.3 ns, ∼0.9 ns respectively, and the mean value of each peak corresponding to the $T_{\rm est}$ is consistent with that of MC setting. But Fig. 4(b) shows three peaks have some overlap, that's because of the poor resolution of MDC time. For 8 ns is the bunch time interval, the event within 4 ns left and right of the peak is judged to belong to that bunch. Otherwise if the $T_{\rm est}$ is more than 4 ns compared with the peak, it will be regarded as the neighborhood bunch. We define the rate of error judgement events as the error rate, as shown in Fig. 4, the error rate is 0.10%.

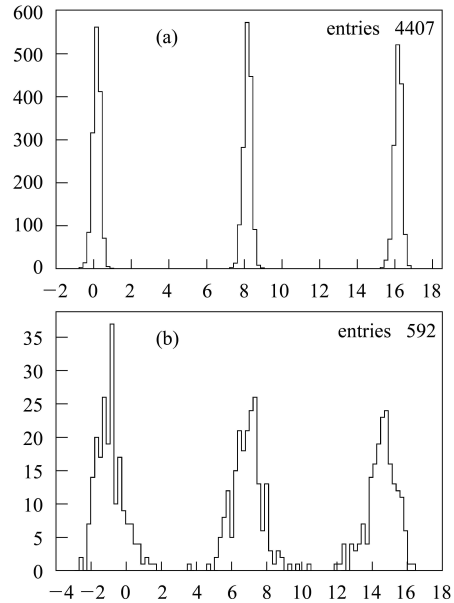

Fig. 4. Preliminary result by TOF(a) and MDC(b).

The same result is got by the single electron events, the efficiency is about 98%. For J/ψ → anything events, which include all J/ψ hadron decay channels, the reconstruction efficiency is 96.4%, the error rate is 0.6%. The reconstruction efficiency is a littel lower. The reason is that the multi-track events with low momentum, small-angle tracks and complex event topology will bring difficulty in track finding and matching.

4 Performance

4.1 To study the capability of rejecting noise

Since BEPCII adopts two rings and multi-bunches and with high luminosity, it is most possible that the noise[10] of BESIII is much higher than BESII. So it is a very hard task for the event start time calculation method to reject the noise. The MDC fast tracking algorithm, which is used to calculate the particle flight time, has almost no ability to reject noise, because it only uses the information of wire position, instead of using the TDC (drift distance) information. If without correct event start time, the following event reconstruction of BESIII will not work correctly. So the efficiency and correctness of $T_{\rm est}$ are required to be as high as possible. One of the most difficult tasks is to improve the ability of reducing noise.

4.1.1 Noise character

The noise level is defined as the ratio of the numbers of noisy sense wires to the total sense wires. In order to simulate the BESIII noise, the BESII experiment data with different energy range, different run time in years and seasons and different collision modes are studied to get the typical distribution of noise. Then this distribution is normalized to BESIII as listed in Table 1. The $T_{\rm est}$ method and the algorithm are studied using different kinds of MC data samples generated with the above noise assumptions.

Table 1. Distribution of noise level.

index of superlayer	1	2	3—4	5	6—11
ratio of noise(%)	10.0	7.0	4.4	2.0	1.0

4.1.2 The influence of noise on the MDC fast tracking and event start time

The results of the event start time program, calculated with different MC data with the noise level from 10% to 50%, show that the effects of the noise on the MDC fast tracking and event start time are very significant. Table 2 shows the results of efficiency of MDC FastTrkAlg and $T_{\rm est}$ algorithm for single track and multi-tracks events at the noise level 30%.

Table 2. The reconstruction efficiency of MDC-FastTrkAlg and $T_{\rm est}$ algorithm for single track and multi-tracks events at the noise level 30%.

event	single track	multi-tracks
Eff. of MdcFastTrk	93%	88%
Recon. Eff. of $T_{\rm est}$	94.4%	95%
error rate of $T_{\rm est}$	3.9%	3%

4.1.3 The methods to reduce noise

To solve the problem of the noise the fast tracking code is tuned very carefully. The following measures are adopted for fast tracking algorithm.

(1) The adjustable parameters are optimized, which include the constraint of difference ϕ of hits used for linking the segments inside a superlayer or between superlayers, the value of χ^2 used for 2-dimension fitting, and the z value used for 3-dimension fitting. After the study, the tracking efficiency of the fast tracking can be improved a little better, but it could not solve all the problems.

(2) Omitting the inner chamber of 8 stereo layers when reconstructing the tracks, since the noise has the largest influence on the inner chamber. The result is that the error rate becomes a little less, but the reconstruction efficiency is not distinctly better.

(3) After studying the character of the segment in each super-layer, the method of fitting the segment with a line and the rejection of the unreasonable segment by constraining the fitting result χ^2 are used.

(4) The circle fitting is performed after the $r-\phi$ tracks built and the bad hits, which have the biggest residual error, are removed.

For event start time algorithm, the following measures are performed to reject the noise.

(1) To increase the $T_{\rm est}$ efficiency calculated by TOF. Considering that the efficiency of the track matching from MDC to TOF is poorer in multi-event case, we optimize the matching method, at first, the good track selection condition for MDC is tightened, then the track is extrapolated to TOF and matched with three adjacent TOF counters instead of exactly one counter as used before.

(2) For MDC part, since TDC and ADC value of noise sometimes are abnormal, we constrain the TDC and ADC value to choose the good hits.

(3) To study a new segment fitting method with least-squared method: assuming the $T_{\rm est}$ of the event is 0 ns, 8 ns and 16 ns respectively, and we do the least-squared fitting using each time, then find the real $T_{\rm est}$ which should have the least χ^2. The $T_{\rm est}$ efficiency is less than the old method due to applying tighter selection cuts for the segment finding and fitting. But it can reduce the error rate by about 0.8%. This method will be studied further for experimental data.

The error rate decreases by about 1% after carrying out the above methods. For electron event with 30% noise, the reconstruction efficiency is 94.6%, and the error rate is 3.0% which is about 0.9% lower than before; For $J/\psi \to$ anything events with 30% noise, the reconstruction efficiency is 95.8%, and the error rate is 2.5% which is about 0.5% lower than before. Although they are better than before, the results are not ideal, so we need to do further study to reduce the rate of wrong determination of $T_{\rm est}$.

Table 3. The $T_{\rm est}$ efficiency of different noise levels after MDC reconstruction.

noise level(%)	0	10—20	30—40	50	60
Recon. Eff.(%)	99.9	99.8	99.8	99.5	99.1
error rate(%)	0.26	0.40	0.88	0.83	0.83

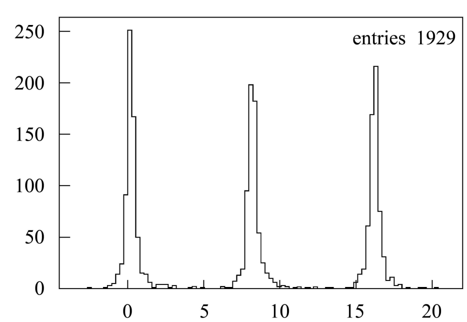

Fig. 5. The result of $T_{\rm est}$ calculated by three methods with $J/\psi \to$ anything events at the noise level 20%. The events generated by MC are 2000, but after trigger selection, the events with charged tracks become 1932, which is the entries that should be calculated.

By studying the character of the events for which the $T_{\rm est}$ is not determined correctly, most cases belong to the events with small angle tracks, large tracking error in MDC fast tracking, the particle misidentification and so on. We find that in most cases those events are very hard to be settled by optimizing the algorithm. So we consider improving the flow of the $T_{\rm est}$ program. The concrete scheme is to calculate the event start time once more after the MDC main reconstruction[11]. By this new scheme, the $T_{\rm est}$ reconstruction efficiency of $J/\psi \to$ anything events reaches above 99%, and the error rate decreases to below 1% for noise level 0—60%. The detailed results are listed in Table 3. Fig. 5 shows the result of $T_{\rm est}$ calculated by three methods with $J/\psi \to$ anything events at the noise level 20%. The only weakness of this new scheme is that the CPU used is somewhat more than before.

4.2 The performance checking of the track reconstruction system

The MDC time measurement is very important in achieving the main function of the precise measurement of the spatial position and momentum of the charged particles in MDC. So the event start time plays an important role in the BESIII event reconstruction[12]. In the BESIII physics analysis, the very hard task is the particle π/K separation, specially in the high momentum case (greater than 1.2 GeV), if the momentum resolution is not good enough to separate the K and π particle, some physics channel is hard to handle, such as the $J/\psi \to K^+K^-, J/\psi \to \pi^+\pi^-$ channel. So this two physics channel is used to check the influence of the performance of time measurement system by the event start time algorithm. At first, the $J/\psi \to$ anything data sample is generated, and the event start time is randomly set at 0 ns, 8 ns, 16 ns. Using the entirety of event reconstruction package, then we do the $J/\psi \to K^+K^-$, $J/\psi \to \pi^+\pi^-$ events selection. Only two charged tracks in the event are required. In this analysis, the most possible background events come from the leptonic decay modes $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ with the branching ratios of 7%, a lesser extent from $J/\psi \to p\overline{p}$ decay which occurs with a branching ratio of about 0.2%, and the other possible background sources are the three-body decays $J/\psi \to \rho^\pm\pi^\pm$ and $J/\psi \to K^\pm K^{*\pm}$ with the branching ratios of 1.0% and 0.34%. The accepted $\pi^+\pi^-$ and K^+K^- pairs are required to have the following characteristics: (1) Two back-to-back(acollinearity less than 5°) oppositely charged tracks. This cut mainly removes the contributions from $\rho\pi$ and KK^* final states. (2) requiring the $E_{\rm SHOWER}/P_{\rm TRACK}$ less than 0.9 for both tracks to remove the events of the type $J/\psi \to e^+e^-$. (3) None or only one of the muon layers is hit. (4) Each track has $|\cos\theta|$ less than 0.93. (5) The measured momenta of both particles satisfy 1.34 GeV/$c < p <$1.75 GeV/c, the lower cut removes $J/\psi \to p\overline{p}$ and the upper cut removes the remaining cosmic ray background. After the above selection, the momenta distribution of $J/\psi \to \pi^+\pi^-$ and $J/\psi \to K^+K^-$ is got as shown in Fig.6. In the figure we can see the two particles π/K are detached clearly.

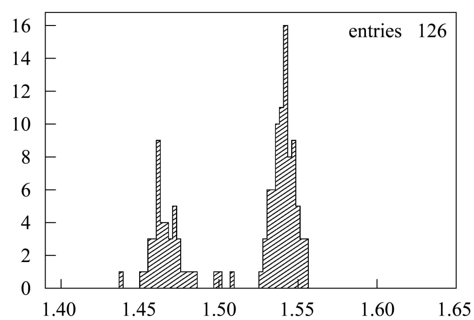

Fig. 6. The momentum resolution of $J/\psi \to \pi^+\pi^-$ and $J/\psi \to K^+K^-$.

5 Conclusion

The event start time algorithm works well from the MC event sample, and achieves the requirements for efficiency and time resolution, especially after the second $T_{\rm est}$ calculation following the MDC reconstruction, the efficiency can achieve above 99% and the error rate can stay below 1% for various noise levels. We still need to do further study for all of these events for which the $T_{\rm est}$ is not determined correctly so far and try to improve the code. After the experimental data are available, the code should be re-optimized and the parameters be tuned for the real data.

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