Cosmic ray test for a T0 detector*

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Abstract: The endcap of time-of-flight (ETOF) detector in BES (Beijing Spectrometer) III is planned to be upgraded by using multi-gap resistive plate chambers (MRPCs) and the designed time resolution of the MRPCs is around 50 ps. Thus a time-zero (T0) detector needs to be built to offer a high quality reference time for the MRPCs beam test. So a T0 detector is built using plastic scintillator tiles (BC420) to couple with four fast phototubes (PMTs, Hamamatsu H6533). The timing properties of the detector is studied by using a cosmic ray test and factors related to the time resolution, such as plastic scintillator size, readout mode and angle effects, are discussed. T0 detector timing resolutions of ∼41–62 ps are achieved, which means that the T0 detector can be used in the MRPC beam test.

Key words: T0, plastic scintillator, PMT, MRPC, ETOF

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1 Introduction

Recently, multigap resistive plate chambers (MRPCs) have attracted much attention and stimulated many studies due to its application in time of flight (TOF) [1]. The time resolution of an MRPC can be less than 67 ps and an efficiency of more than 97% can be achieved [2]. In addition, MRPC can be highly segmented with different pads to cope with the high multiplicity expected in e-p collisions. So research on the upgrade for the TOF of BESIII with MRPC is under way. The time resolution is designed to be ∼50 ps in this type of MRPC and each MRPC module during the R&D period is segmented with very small pads. The beam test of such MRPCs need a high quality time-zero (T0) detector with a small effective area to offer the reference time and to deal with the pad efficiencies.

T0 detector is usually built by using small plastic scintillator tiles to couple with photomultiplier tubes (PMTs) and many papers have studied them. The T0 detector depicted in one paper [3] has a time resolution of 76 ps, for which the plastic scintillator is used (BC420). In the Ref. [4], the author reports that a time resolution of 60 ps can be realized by using a plastic scintillator (BC408) and Ref. [5] studied the timing property of different kinds of plastic scintillators and the time resolution was in the range of 45 to 60 ps.

This paper reports a T0 detector built with plastic scintillator (BC420) tiles to couple with the PMTs (Hamamatsu H6533) [6] and a cosmic ray test is done on the timing properties of this T0 detector.

According to the Atwood formula [3], the time resolution (σ) of a scintillator to couple with PMTs is defined as:

$$\sigma = l/\sqrt{N_{\text{pe}}}\,. \qquad (1)$$

Here l is the length of the light transmission path in the scintillator and N_{pe} is the average number of

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photo-electrons received by the PMT. Generally, a thick plastic scintillator is useful for photoelectron generation, thus leading to a small value of σ. Therefore, in order to obtain a high time resolution, the scintillator tiles should not be too thin.

The MRPC for the TOF upgrade in BESIII will be tested by the beam consisted of pions, protons and electrons with the momentum around 600 MeV/c. When the beam passes through the T0 detector, there are particle annihilation, bremsstrahlung and multiple scattering rates. To suppress the rates of beam momentum loss, the plastic scintillator tiles used for the T0 detector should not be too thick. A Monte carlo simulation is used on the plastic scintillator thickness effect to the beam momentum loss. It indicates that after four 5 mm plastic scintillator (BC42) tiles, the momentum loss of 600 MeV/c beam will not be more than 2.5% and 1.7% for electrons and pions, respectively. Therefore, the plastic scintillator tiles are chosen to be 5 mm thick. In addition, the diameter of the PMT (H6533) is 20 mm, it is convenient to deal with each scintillator tile as being 20 mm wide.

This paper is organized as follows: Section 2 describes the experimental set-up; the experimental results of cosmic rays will be discussed in Section 3 and in the last section, a conclusion is given.

2 The experimental set-up

BC420 is a kind of fast plastic scintillator with a rise time of 0.5 ns and a decay constant of 1.5 ns [4]. The PMT (H6533) has good time characteristics with 0.7 ns rise time, 10 ns transit time and 0.6 ns transit time spread [6]. To study the timing properties of the T0 detector, two kinds of 5 mm thick scintillator tiles with different areas are chosen. One is 5 mm × 20 mm × 80 mm for charge division readout (CDR) from both ends and the other is 5 mm×20 mm×70 mm for single end read out (SER) from one of the two ends. All the plastic scintillator tiles are polished and wrapped with aluminum foil to collect as much scintillation light as possible.

The upper panels in Fig. 1 (a) and (b) show the schematic diagrams of the T0 detector with the CDR and SER modes, respectively. For each readout mode, two identical frames are used and each frame can fix a pair of PMTs. The lower panels of Figs. 1 (a) and (b) show two frames viewed from different directions, which corresponding to the CDR mode and SER mode, respectively. In the SER mode arrangement, the distance between the two plastic scintillator tiles is 5 mm in the same frame and the distance L between the two frames for both of the SER and CDR mode can be adjusted easily on a platform. The coincidence signal between the four PMT outputs determines the timing properties of the T0 detector and a particle passing through all of the scintillator tiles of the two frames will cause a such signal. Obviously, the effective area of the plastic scintillator tiles will determine the efficiency of the detector.

In the experiment, the time resolutions of the T0 detector are studied with L equal to 19 cm for the

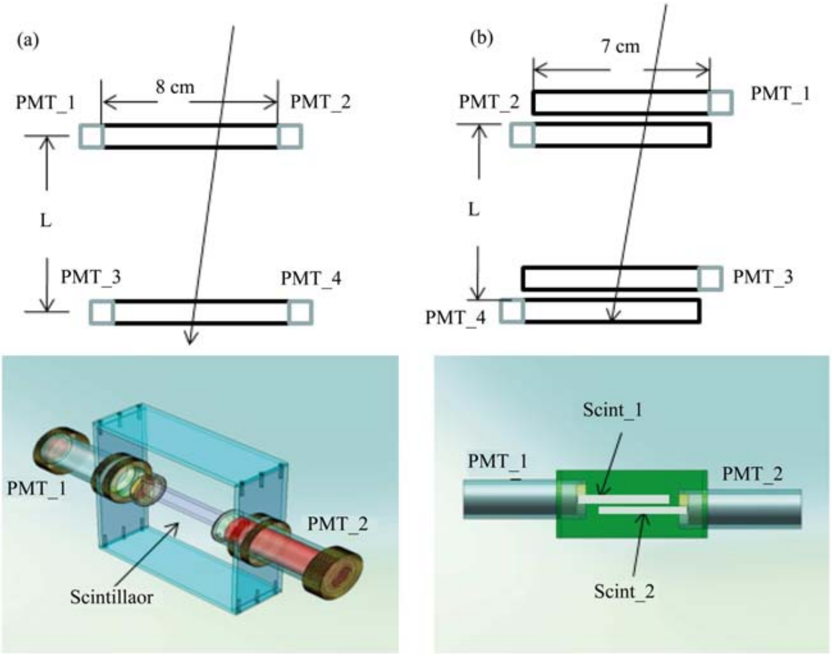

Fig. 1. T0's different read-out mode schematic diagrams and mechanical diagrams. (a) Charge division read out; (b) Single end read out.

CDR mode and 0.5 cm, 5 cm and 19 cm for the SER mode. Together with such a T0 detector, a STAR MRPC [7] with a time resolution of 100 ps is measured in a cosmic ray test and it is intended to check whether the T0 detector work well or not. In the cosmic ray test, the STAR MRPC is placed below the T0 detector for the L equal to 0.5 cm and in the middle of the two frames for the L equal to 19 cm. The T0 detector and the STAR MRPC are all placed horizontally in order to accept the cosmic rays vertically as much as possible.

The T0 detector with L equal to 0.5 cm is first tested in the laboratory by using cosmic rays and its electronic schematic is shown in Fig. 2. Schematically, each signal out of the PMTs is split into two parts by a FIFO (Lecroy 428F). One is sent into QDC (Caen V965) for measurement. The other is discriminated by a discriminator (Lecroy 623B). The four signals from the discriminator are sent into a TDC (Caen V1290N) for measurements and two coincidental signals are generated by these four equivalent signals using a logic unit (Lecroy 365AL). The trigger for the TDC and the QDC gate are given by the two coincidental signals from the logic unit. In the laboratory test, the cables' contribution to the time resolution can be ignored because of their short lengths.

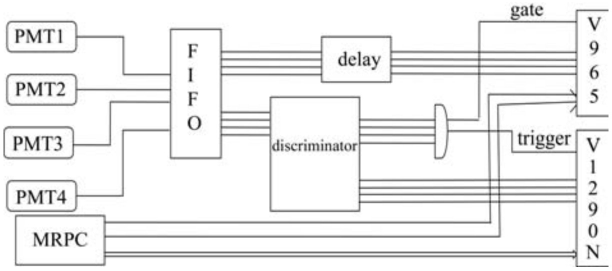

Fig. 2. Scheme of the readout system.

The T0 detector is aiming to built for the MRPC beam test, therefore the beam test electronic system will contribute to the time resolution. There is a long distance between the test position and the electronic system position. So additional long cables around 40 m to 50 m are used to transmit the signals from the PMTs of the T0 detector. In order to protect the NIM signals against deformation, the signals before being sent into the TDC and logic unit will be discriminated two times at the both ends of the long cables. The Star MRPC as a reference standard detector is tested by sending its signals into the corresponding QDC and TDC after a preamplifier.

3 The experimental result

3.1 The method of data analysis

For the four PMTs, the time interval recorded by the TDC are defined as t_i $(i=1,2,3,4)$, and the integrated charge values of the signals measured by QDC are defined as Q_i $(i=1,2,3,4)$. It should be noticed that V1290N can realize a time resolution of 25 ps, but the trigger-timing stamp comes from its module clock cycled every 25 ns. Therefore, the distributions of t_i $(i=1,2,3,4)$ are all around 1000 channels (25 ns). In order to subtract the module clock contribution for each channel measurement, the time T_i $(i=1,2,3,4)$ for each PMT measured can be defined as:

$$T_1 = t_1-(t_3+t_4)/2, \tag{2}$$

$$T_2 = t_2-(t_3+t_4)/2, \tag{3}$$

$$T_3 = t_3-(t_1+t_2)/2, \tag{4}$$

$$T_4 = t_4-(t_1+t_2)/2. \tag{5}$$

The reference time $T0$ and the time interval of the MRPC T_{mrpc} relative to the $T0$ are defined as:

$$T_0 = (t_1+t_2+t_3+t_4)/4, \tag{6}$$

$$T_{\text{mrpc}} = t_{\text{mrpc}}-T_0. \tag{7}$$

Here t_{mrpc} is the recorded counts of TDC for the MRPC. Eq. (7) shows that a small value of T_0 is important for the high quality time resolution test of MRPC.

According to the error propagation law:

$$\sigma(T_0)=\sigma[(T_1+T_2-T_3-T_4)/4], \tag{8}$$

$\sigma(T_0)$ indicates the intrinsic resolution of the reference time $T0$. Thus attention can be focused on the value of $\sigma(T_0)$ in experiments.

The leading edge discrimination in experiments can cause time walk and it can be corrected by the Eq. (9) [8]:

$$T_i=\alpha_{i,1}+\frac{\alpha_{i,2}}{\sqrt{Q_i}}+\frac{\alpha_{i,3}}{\sqrt{Q_i^2}}+\frac{\alpha_{i,4}}{\sqrt{Q_i^3}}+\frac{\alpha_{i,5}}{\sqrt{Q_i^4}}. \tag{9}$$

Here Q_i $(i=1,2,3,4)$ and T_i (i=1, 2, 3, 4) have the same meaning as above and $\alpha_{i,j}$ (i=1, 2, 3, 4; j=1, 2, 3, 4, 5) are the free parameters determined by the least-square fit. Fig. 3, as an example, shows the time distribution and time versus amplitude scatter plots without and with correction of the PMT1 of the SER mode. Without correction, the time resolution, in Fig. 3(a), is around 369 ps and, with correction, the time resolution is around 155.7 ps as shown in Fig. 3(c).

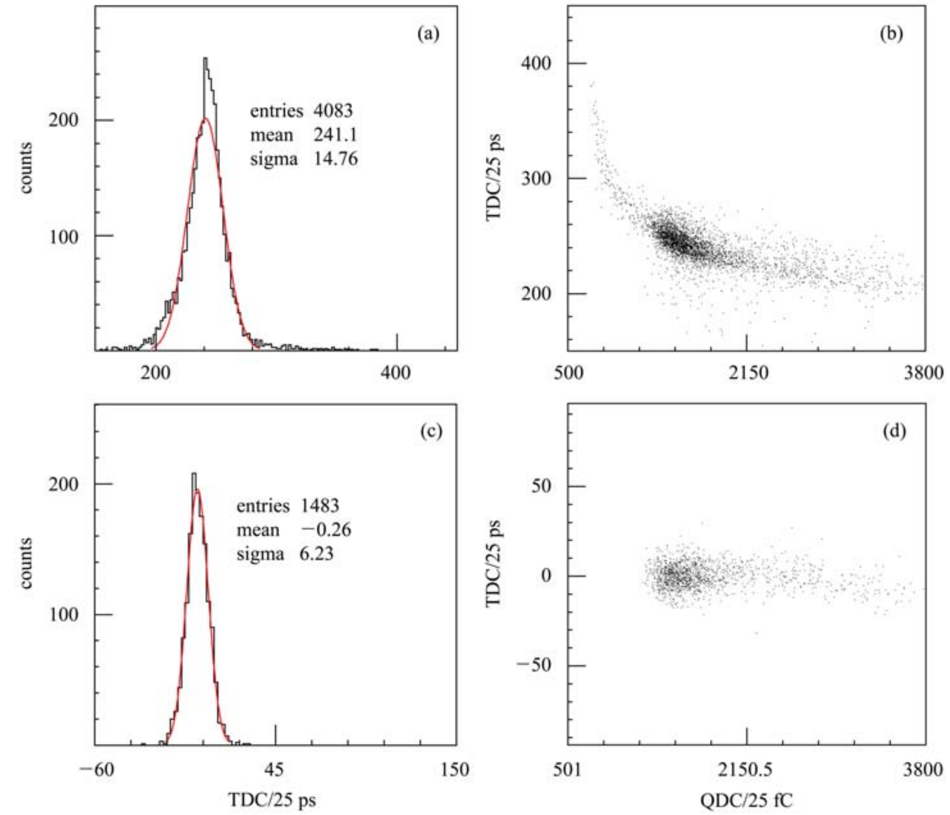

Fig. 3. Time distribution and time vs. amplitude scatter plots with no correction:(a), (b) and with correction:(c), (d).

3.2 Time resolution measurements

In the laboratory cosmic ray test, the T0 detector of the SER mode is tested with L equal to 0.5 cm. The time resolution $\sigma(T_0)$ is 40.9 ps, which is shown in Fig. 4 (a) and listed in the first row of Table 1. The same setup is tested with the beam test electronic system by using cosmic rays and the time resolution is 46.9 ps and listed in the second row of Table 1. It indicates that the same setup has different time resolutions, which is caused by the different lengths of cables and the signal discrimination times.

Table 1. Different readout mode tests for T0 equipment with results of the STAR MRPC.

L/cm	$\sigma(T_0)$/ps	$\sigma(T_{\mathrm{mrpc}})$/ps	readout mode
0.5	40.9±0.5	none	single(laboratory)
0.5	46.9±0.9	none	single
5.0	49.5±1.1	104.4±3.0	single
19.0	57.0±2.0	108.2±7.1	single
19.0	62.8±1.8	111.3±6.9	double

Using the beam test electronic test system, the T0 detector is tested along with a pad of the STAR MRPC at L equal to 5 cm and 19 cm. The results are listed in the third and fourth rows of Table 1. As an example, the time distribution of the STAR MRPC is plotted in Fig. 4 (b), which is tested by the T0 detector with L equal to 19 cm. The time resolution of the T0 detector can reach 49.5 ps and 57 ps at L equal to 5 cm and 19 cm, respectively, and the results of the STAR MRPC is consistent with the Ref. [7].

The CDR mode is also studied with the beam test electronic system by using cosmic rays and, like the SER measurements, the STAR MRPC pad is tested at the same time. The last row of Table 1 show the time resolutions of the T0 detector and the MRPC. It indicates that the time resolution of CDR mode is around 62.8 ps, which is a little larger than the values of SER mode measured above, but the time resolution of the STAR MRPC is nearly the same value as tested by the T0 detector of SER mode.

It can be found that the time resolution of the SER mode is better than the counterpart of the CDR mode. According to Eq. (1), it may be mainly caused by the different number of photoelectrons collected by PMTs. Supposing the incident particles are the same in per unit time for the SER mode and CDR mode, and supposing the scintillation lights are all received by PMTs. Since the thicknesses are the same, particles passing though a plastic scintillator tile in per unit time should cause the same photons generated in the scintillator tile, but these photons are collected by only one PMT in the SER mode and by two PMTs for the CDR mode. So the number of photoelectrons of the SER mode is larger than the number of the CDR mode. Actually, the scintillator tiles of the CDR mode are longer than that of the SER mode, according to Eq. (1), the length of the different scintillator tiles is another factor that causes the different time resolution. In the following Section, it can be found that the incident angle of particles will also affect the time resolution.

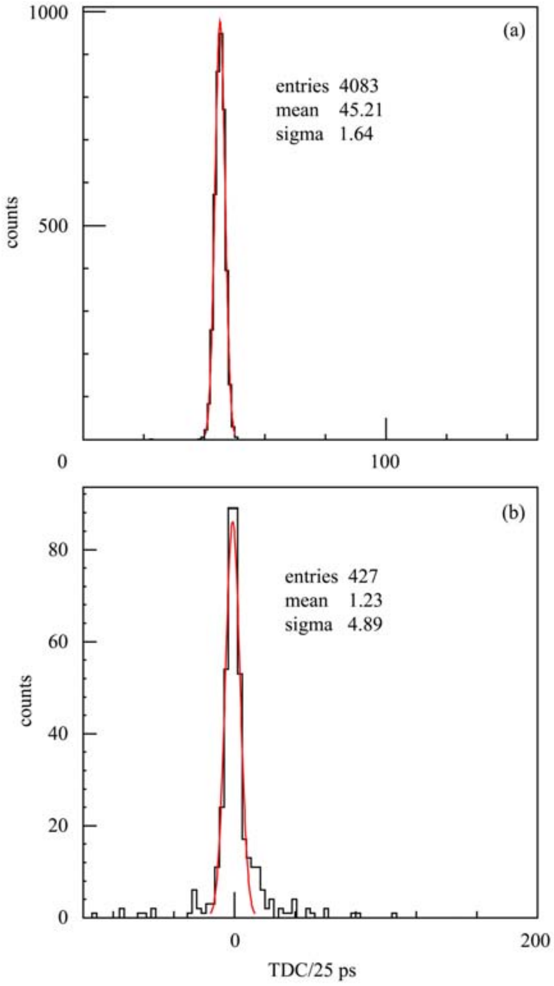

Fig. 4. Time resolution of T0 with L equal to 0.5 cm (a) and time resolution of STAR MRPC (b).

In the MRPC beam test for the TOF of the BESIII upgrade, most of the incident events are single particle events. The scintillation photons are nearly constant with the same thickness of plastic scintillator tiles (BC420), so longer scintillator tile will cause a large time resolution. Therefore, short plastic scintillator tiles are desirable.

3.3 Angle effects of incident particles

Now we discuss the angle effects of incident particles for the SER mode of the T0 detector. The distances between the particle hit positions and the PMTs are supposed to be l_1, l_2, l_3 and l_4 corresponding to the PMT1, PMT2, PMT3 and PMT4, respectively. Then an approximation equation is derived:

$$(t_1-t_2)-(t_3-t_4)=\frac{2}{v}\times(l_1-l_3). \tag{10}$$

Here, v is the velocity of scintillation light transmission in the scintillator. In Eq. (10), the time of particle flight between the plastic scintillator tiles in the same frame is ignored. The value of $|l_1 - l_3|$ can be considered as the approximate deviation from the particle first hit to the last hit at the T0 detector and this value is caused by the incident particle angle. From the error propagation law, $(t_1-t_2)-(t_3-t_4)$ is related to the time resolution of $\sigma(T_0)$. Fig. 5 shows the distribution of $(t_1-t_2)-(t_3-t_4)$ of the SER mode with L equal to 0.5 cm.

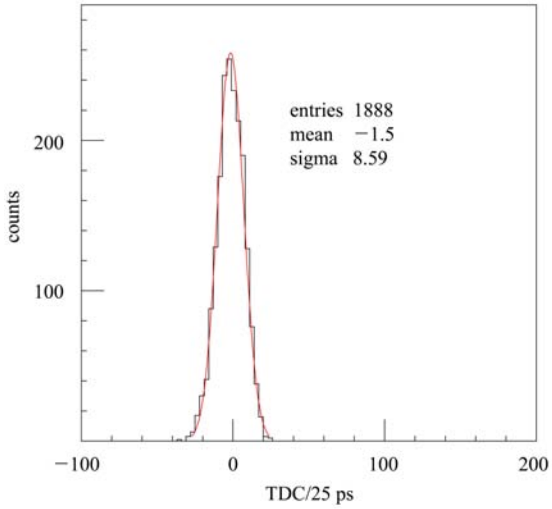

Fig. 5. The distribution of $(t_1-t_2)-(t_3-t_4)$ fitted with Gauss function.

Table 2 shows the standard deviation of the distribution of $(t_1-t_2)-(t_3-t_4)$ for the SER mode of the T0 detector. It shows that the $\sigma[(t_1-t_2)-(t_3-t_4)]$ also varies with L changing and its value become small as the L decreasing. For L equal to 0.5 cm the channel value is 8.6, corresponding to the $\sigma[(t_1-t_2)-(t_3-t_4)]$ of 215 ps.

Table 2. The distribution resolution of $(t_1-t_2)-(t_3-t_4)$.

L/cm	$\sigma[(t_1-t_2)-(t_3-t_4)]$/channel	readout mode
19.0	12.3±0.5	single
5.0	11.3±0.2	single
0.5	8.6±0.1	single

Obviously, the trend of $|l_1-l_3|$ is the same as the time resolution of $\sigma(T_0)$. For a fixed angle, the time resolution becomes large as the value of L increases. In fact, as the distance L raised, the difference of $|l_1-l_3|$ becomes significant, so the time resolution or the $\sigma[(t_1-t_2)-(t_3-t_4)]$ become worse.

4 Conclusions

A T0 detector is built by using different sizes of plastic scintillator to couple with PMTs and factors relating to the time resolutions of the T0 detector are discussed in cosmic ray tests. The results show that the T0 detector can achieve time resolution of ∼41 ps in the laboratory test and of ∼46.9–62.8 ps by using the beam test electronic system. It indicates that the T0 detector can fulfill the timing requirement of the MRPC beam test for the TOF of BESIII upgrade.

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