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NUCLEAR SCIENCE AND TECHNIQUES

Nuclear Science and Techniques, Vol.18, No.3 (2007) 164–171

A time-over-threshold technique for PMT signals processing

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Abstract A novel front-end circuit designed for PMT signals processing considering the solution of “Time Walk” correction is discussed in this paper. We are trying to apply the TOT (Time over Threshold) technique to our research. Different from traditional ways, where amplitude is measured, time width is measured for slew correction here, which takes the advantage of TDC. Expensive fast ADCs are abandoned and the whole time measurement electronics design becomes more effective and economical. Test boards have been developed and a convenient method is introduced to evaluate our TOT technique. Results have shown that a 10ps slew correction resolution is achieved throughout the amplitude range from -108mV to -2000mV for negative signals of both 5 ns leading and trailing edge with 10 ns 50%-50% pulse width.

Key words Time over threshold, Time measurement, Slew correction, PMT, HPTDC, Variable thresholds discrimination

CLC numbers TM935.45, TM935.41, TL822, TN911.71

1 Introduction

“Time Walk” is an inherent problem to time measurement discriminated with a preset threshold. To obtain the best time resolution, timing compensation should be made due to different signals. Traditionally, ADC (amplitude-to-digital converter) is employed to get the pulses’ amplitude information which can be used to calibrate the time of the hit recorded by TDC (time-to-digital converter), referred as T(A) correction. But a fast ADC consumes more power and costs more than a TDC. To achieve an effective design, TOT technique was introduced by CERN (European Laboratory for Particle Physics) to treat MRPC (Multi-gap Resistive Plate Chamber)[1] pulses in ALICE Collaboration.[2] TOT measures no signal amplitude but width which can also be used to perform slew correction, referred as T(time width) correction. This can be seen from the illustration of time-over-threshold in Fig.1. For the same leading time, the larger signal has faster slew rate and wider time width.

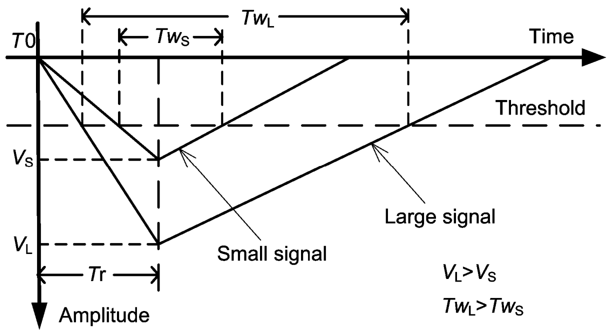

Fig.1 Illustration of time-over-threshold.

Fig.2 gives the diagram of TOT technique in ALICE project.[3] The TOT board is placed near MRPC to receive better analog MRPC signals. Positive output of the preamp is directly sent to the comparator while the negative output to the integrating circuit. Differential discrimination is adopted so as to get better time information of the leading edge, which is the principal purpose of time measurement. Output

Supported by National Natural Science Foundation of China (10405023) and National Large-Scale Science Project BEPCII

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Received date: 2006-11-01

of TOT board will be transmitted differentially to the readout electronics board and HPTDC (high performance TDC)[4] measures both the times when leading edge and trailing edge arrive, thus time width (trailing edge - leading edge) can be obtained. HPTDC has a 25ps time resolution before further calibration but also an 8ns dead time. The integrating circuit inserted to insure that the output of discrimination has a width greater than 8 ns, otherwise the time of the trailing edge will not be measured. Meanwhile, wider range of time width would be obtained after extended.

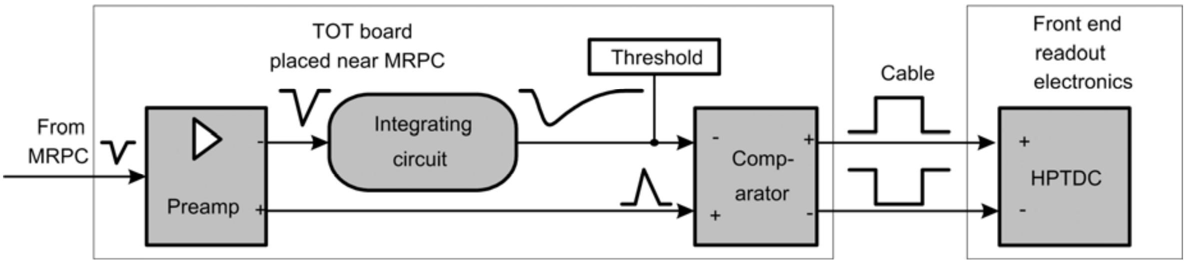

Fig.2 Diagram of TOT technique at Alice.

Combined with scintillation detectors, PMTs (Photo Multiplier Tube) are widely used by nuclear and particle physics experiments nowadays.[5] Similar to MRPC, we can also bring the TOT technique into signals processing of PMT. But the two situations are obviously different: signals and noises coming from PMT are much larger than those from MRPC. Negative PMT pulses can be -2000mV, while MRPC signals are normally smaller than -100mV. Large amplitude and noise would bring further problems, which will be discussed in a later section. The TOT circuit should be reconsidered specially for PMT signals.

2 Application of TOT technique to PMT signals

2.1 Basic TOT circuit for PMT signals

With some improvements against the large signals, the TOT circuit diagram shown in Fig.2 should be applicable to PMT pulses, because the pulses coming from MPRC and PMT are similar. As to the preamp, we need to use a rail-to-rail amplifier to accept the wide range of PMT pulses. And it should have wide bandwidth so that it would not slow down the PMT pulses. High input resistance is also required for better impedance match. Some current feedback amplifiers meet these requirements but they have no differential output. Therefore we have to add a high-speed differential driver, such as AD8131 and THS4503, etc.. For current feedback amplifier, we choose THS3201.

Fig.3 shows our TOT technique diagram for the test board’s design. Negative pulses generated by Agilent 33250A will perform as the PMT output. HPTDC is still adopted on the time measurement board which is designed as a VME 9U module.

A dual-channel ultra-high-speed comparator MAX9601 is selected for discrimination. To reduce filter noises, a high level threshold discrimination circuit is provided. The time is measured whenever the signal passes the high level threshold. In order to keep the leading edge of low-level threshold discrimination, the output of high-level threshold discrimination should be stretched while that of low-level threshold discrimination should be delayed. The waveform given in Fig.3 shows the relationship of each signal. MC100EP195 is used for time delay while a D flip-flop is employed to establish the time stretch circuit. The RESET pin of D flip-flop is controlled by the voltage of the capacitor, which will reset the Q output after a certain time when Q jumps to high value. Actually it acts as a monostable pulse generator with the characteristic time C1*R1. This must be carefully selected in respect that the $\bar{Q}$ output is supposed to be wide enough to cover any signal of low-level threshold discrimination.

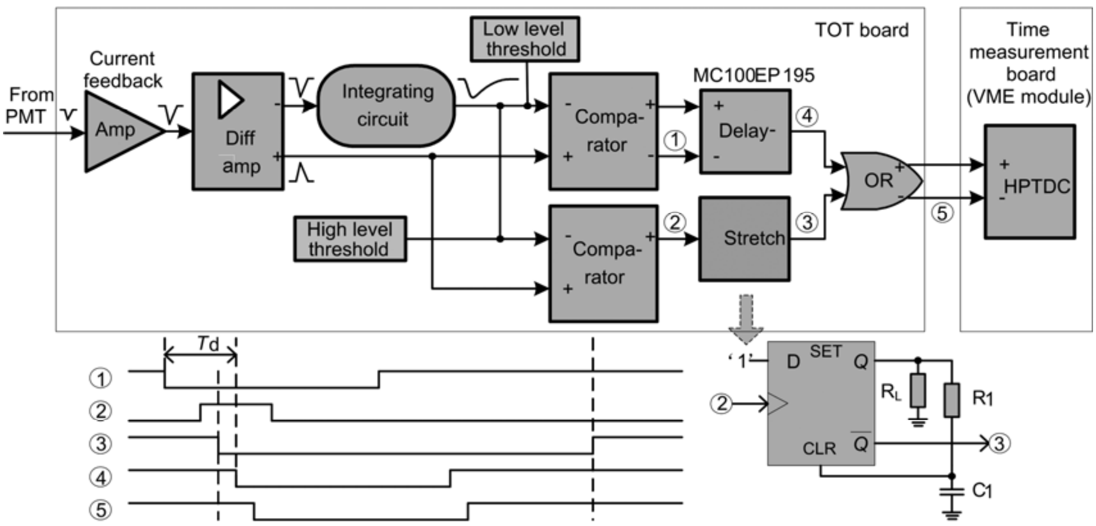

Fig.3 Basic diagram of TOT technique for PMT signals.

2.2 The integrating circuit

We still need an integrating circuit, because PMT pulses are very narrow. The integrating circuit should have the ability to accept negative pulse input from -100mV to -2000mV. What we want is wider and larger signals for discrimination. But once the leading time and amplitude is specified, the wider the signal is, the more slowly its trailing edge rises. Noises will bring great jitter to the time when the trailing edge passes the low level threshold. The integration is acceptable once the time width of the pulse which has just overcome the high level threshold discrimination becomes larger than 10ns.

With a view to less power consumption and simpler design, we established an integrating circuit for PMT signals utilizing only two transistors, as is given in Fig.4. It has a two-stage current-parallel negative feedback structure. It can be analyzed in the way of feedback loops to get the Laplace transform of transfer function $h(t)$, always represented as Eq.(1).

$$H(s) = H(0)/[(1-s/P_1)(1-s/P_2)] \qquad (1)$$

where $H(0)$ is the low frequency voltage gain, P_1 is the frequency pole due to the high-frequency effect of Q1 while P_2 is brought in by Q2.

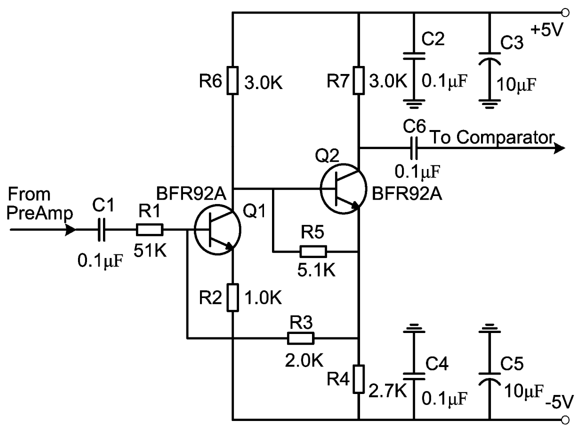

Fig.4 Integrating circuit.

Frequency poles can be easily estimated by the model shown in Fig.5. It is derived from the hybrid pi model of bipolar junction transistors.[6] It consists of an input impedance r_{in}, an output impedance r_o and a voltage controlled current source described by the transconductance g_m. In addition, it contains a simplified capacitor C_i which represents the overall diffusion capacitance and junction capacitance, such as base-emitter capacitance, and the base-collector capacitance, also referred to as the Miller capacitance. The capacitances will slow down the signals while transistor itself will amplify the input current. So the integrating signals without amplitude attenuation can be obtained.

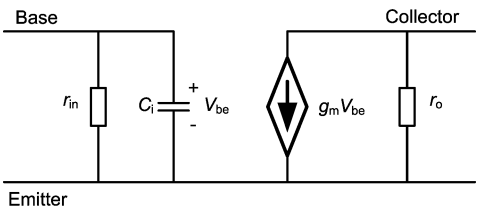

Fig.5 Simplified model of transistor for high frequency.

Fig.6 gives one test wave captured by Tektronix TDS7104 for this integrating circuit. The input signal has both 5ns leading edge and trailing edge with 10ns width (50%-50%). A long tail is formed in the integrating signal. Its trailing edge rises very slowly because of the exponential discharge of the integrating circuit.

2.3 Variable thresholds discrimination

Till now, our TOT technique is still incompetent for application. For signals with amplitude -1000mV, the TOT output has a time width of 105.9ns with 2.257ns RMS. Noises really bring too much jitter to the trailing edge, which is more apparent for large signals. As the discrimination is differential, one simple way to improve this is lowering the voltage at the plus input of comparator so as to let the trailing edge reach the threshold earlier. But this is opposite to the obtainment of better time information of the leading edge. An ideal solution is that we may use different thresholds for discrimination: for leading edge the threshold is low and that for trailing edge is even lower. With adding a feedback branch to the basic circuit shown in Fig.3, we accomplish this, as is specified in Fig.7.

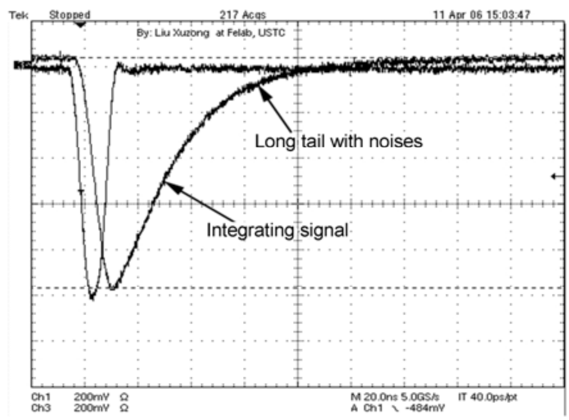

Fig.6 Integrating signal.

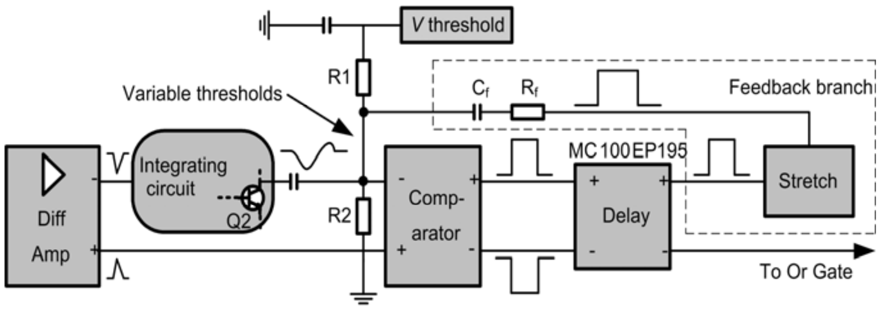

Fig.7 Adding the threshold feedback branch.

The feedback branch contains a resistor, a capacitor and a pulse stretch circuit, the same as described above. When the positive output of MC100EP 195 jumps to high value, the stretch circuit is triggered and generates a 50 ns positive pulse, which is coupled to the low level threshold circuit and charges the junction capacitance of Q2. Actually, this is another R-C integrating circuit. Voltage at the minus input of comparator will then be raised. The actual low level threshold for the trailing edge discrimination becomes lower. The trailing edge of the integrated signal reaches the low level threshold much faster than before. Although the signal becomes narrower somehow, stability of the trailing edge is dramatically improved when it passes the threshold and much better accuracy of time width is achieved. Little variation of time will be caused by noises. From the same input in Fig.4, an integrating signal is shown in Fig.8, with smooth trailing edge, which rises above the low threshold level. Thus, another trailing edge is formed by the discharge of threshold circuit when the positive output of MC100EP195 returns to low level.

This can be named as "variable thresholds discrimination" because the actual value of low level threshold for the trailing edge depends on the signal itself. It gets lower while the integrating signals get larger. The trailing edge of small signal will reach the threshold within a short time, so the voltage of the threshold circuit raised by feedback branch at this moment will be less than that of large signals. The larger the signal is, the greater it is raised. But this tendency will slow down for large signals below -1000mV, for the charge of the threshold is also exponential. It increases little after about 30ns of charging.

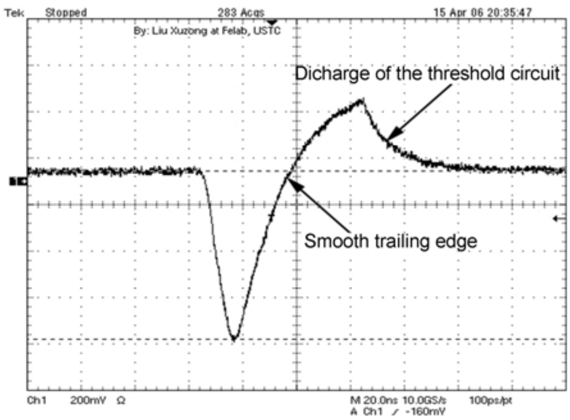

Fig.8 Integrating signal of variable thresholds discrimination.

3 Test results of our TOT circuit

We have tested the input pulse in Fig.4 from -100mV to -2000mV with a step of 5mV. Differential low threshold is set at 40mV and high threshold at 100mV. The relationship between time width and amplitude is shown in Fig.9. And the relationship between time width RMS and amplitude is shown in Fig.10. The relationships in both figures are obvious logarithmic. That is reasonable because of the exponential integration.

In the width-amplitude curve, there is a saddle from -300mV to -800mV. This is because the exponential charge introduced by the feedback branch. When the input pulse is small, time for the charging of the threshold circuit is short before the trailing edge reaches the threshold. As the pulse becomes larger, the charge increases dramatically because it is exponential. So time width decreases much apparently in this area.

In the RMS- amplitude curve, a saddle begins at -300mV, but the RMS runs up again at about -500mV. The reason is that the threshold circuit has been raised about the same value of signal amplitude around this point. The trailing edge passes the threshold near the bottom of the signal, where the slope is very gentle. When the pulse gets larger, the tendency of RMS returns to normal, then the other saddle is formed. The RMS maintains at about 90ps from -1000mV, for the effect brought by the charge of threshold circuit and that of the gentle slope are both not obvious when the trailing edge passes the threshold. These two reverse factors counteract each other and come to a balance.

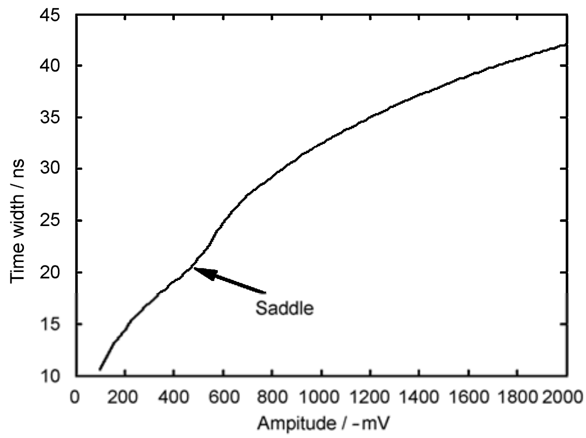

Fig.9 Time width vs. amplitude.

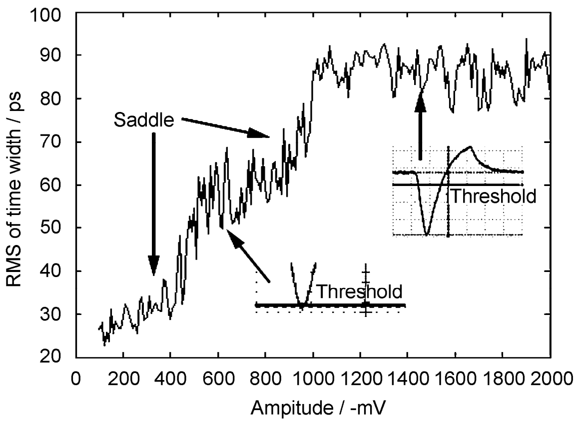

Fig.10 RMS of time width vs. amplitude.

4 One way to evaluate TOT technique

The ultimate purpose of TOT technique is to use the time width for slew correction. What we are pursuing is higher accuracy of time width, and a wider time width and a smaller RMS shall meet this requirement. Here we define some symbols first:

$T0$: time the particle penetrates PMT;

$T1$: time when the leading edge arrives at HPTDC;

$T2$: time when the trailing edge arrives at HPTDC;

$T\mathrm{w}$: time width of signal above the variable thresholds, $T\mathrm{w} = T2 - T1$;

t : slew correction value that should be subtracted from T1 so as to get the intrinsic hit time, $t = T1 - T0$.

From our test result analyzed above, we know that the relationship between time width and amplitude is very complex but not linear. So the relationship between time width $T\mathrm{w}$ and t will not be linear either. We may work out a mapping function between them, but discrete parameters of chips, temperature, voltage and so on will bring uncertainty to it. Actually a much better way is using the look-up-table to be evaluated for T (time width) correction. Once $T\mathrm{w}$ is known, we can get t through one-to-one mapping, $T\mathrm{w} \Rightarrow t$. The most important parameter of this look-up-table is the effective resolution of t, noted as Δt_{e}. Smaller Δt_{e} represents better resolution of time measurement. But unfortunately, Δt_{e} is not a constant in our design but will vary with the time width. This is also caused by the non-linear relationship between $T\mathrm{w}$ and t. We are now trying to find out Δt_{eM}, which is the maximum of Δt_{e} throughout the range of $T\mathrm{w}$. Δt_{eM} represents the worst case of measurement, so it is reliable to use Δt_{eM} for evaluation of the TOT technique.

Assume $T\mathrm{w}_i$ and $T\mathrm{w}_{i+1}$ are two adjacent elements in the look-up-table with a slew correction resolution of Δt. The corresponding input signal of $T\mathrm{w}_i$ is signal A and that of $T\mathrm{w}_{i+1}$ is signal B, as shown in Fig.11. In the practical application, the time width of every signal coming from PMT is uncertain due to miscellaneous noises and interference. The effective resolution Δt_{e} of test will not be as good as Δt in such way. Actually the time width obeys the Gaussian distribution. For signal A, the distribution of its time width $T\mathrm{w}_{\mathrm{a}}$ is $N(T\mathrm{w}_i, \sigma_{\mathrm{Ta}}{}^2)$. Similar, that of $T\mathrm{w}_{\mathrm{b}}$ is $N(T\mathrm{w}_{i+1}, \sigma_{\mathrm{Tb}}{}^2)$. Here we define the following variables:

$$TD_{\mathrm{a}} = T\mathrm{w}_{\mathrm{b}} - T\mathrm{w}_{\mathrm{a}} \tag{2}$$

$$TD_{\mathrm{i}} = T\mathrm{w}_{i+1} - T\mathrm{w}_i \tag{3}$$

$$\sigma_{\mathrm{TD}}{}^2 = \sigma_{\mathrm{Ta}}{}^2 + \sigma_{\mathrm{Tb}}{}^2 \tag{4}$$

TD_{a} will obey the Gaussian distribution $N(TD_i, \sigma_{\mathrm{TD}}{}^2)$, because it is the subtraction result of $T\mathrm{w}_{\mathrm{b}}$ and $T\mathrm{w}_{\mathrm{a}}$. For any numeric M, the probability of $TD_{\mathrm{a}} > M$ is:

$$\mathrm{P}(TD_a > M) = 1 - \phi\left(\frac{M - TD_i}{\sigma_{\mathrm{TD}}}\right) \tag{5}$$

If M=0, then:

$$\mathrm{P}(TD_a > 0) = 1 - \phi\left(\frac{0 - TD_i}{\sigma_{\mathrm{TD}}}\right) = \phi\left(\frac{TD_i}{\sigma_{\mathrm{TD}}}\right) \tag{6}$$

Define judging factor λ as:

$$\lambda = \frac{TD_i}{\sigma_{\mathrm{TD}}} = \frac{T\mathrm{w}_{\mathrm{i+1}} - T\mathrm{w}_i}{\sqrt{\sigma_{\mathrm{Ta}}{}^2 + \sigma_{\mathrm{Tb}}{}^2}} \tag{7}$$

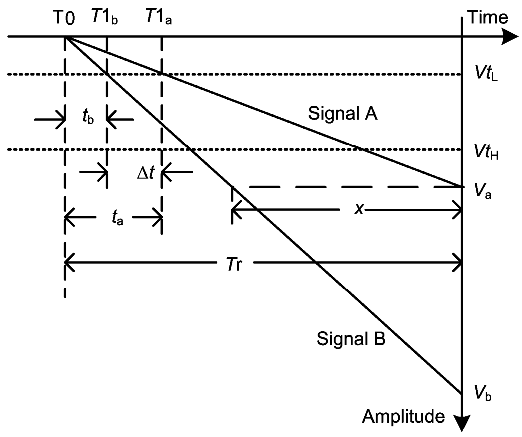

Fig.11 Illustration of slew correction.

From Eq. (6), we can know that if λ grows up, the probability of TD_{a} falling near TD_i will get larger. Then the probability of confusing signal A and signal B will decrease. So Δt_{eM} can be obtained from the signal with the smallest λ. Actually once we have known the amplitude of signal A and signal B, the four parameters in Eq. (7) can be obtained from test. $T\mathrm{w}_i$ is the mean value of $T\mathrm{w}_{\mathrm{a}}$ and $T\mathrm{w}_{i+1}$ is that of $T\mathrm{w}_{\mathrm{b}}$; σ_{Ta} is the RMS of $T\mathrm{w}_{\mathrm{a}}$ and σ_{Tb} is that of $T\mathrm{w}_{\mathrm{b}}$. For every signal A shown in Fig.11, the amplitude of signal B meets the following equations, where we regard the front edge of the test pulses as linear:

$$\frac{V_{\mathrm{b}}}{V_{\mathrm{b}}-V_{\mathrm{a}}}=\frac{T\mathrm{r}}{x} \tag{8}$$

$$\frac{x}{\Delta t}=\frac{V_{\mathrm{a}}}{Vt_{\mathrm{L}}} \tag{9}$$

V_{b} is resolved out as:

$$V_{\mathrm{b}} = V_{\mathrm{a}}Vt_{\mathrm{L}}T\mathrm{r}/(Vt_{\mathrm{L}}T\mathrm{r}-V_{\mathrm{a}}\Delta t) \tag{10}$$

Vt_{L} is set at 40mV in our tests, and Tr is 5000ps. By interpolating the test results, we calculate the relationship between λ and V_a for a look-up-table with Δt =10ps throughout the amplitude range, as is drawn in Fig.12. From the curve we know that small signals have small λ, and Δt_{eM} is located at the smallest signal(-100mV). Better effective resolution of slew correction can be achieved for large signals.

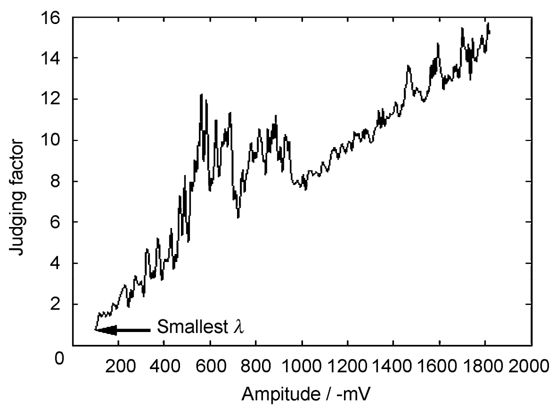

Fig.12 Judging factor λ vs. amplitude.

Now we need to calculate Δt_{eM}. The ENOB (Effective Number of Bits) idea in the ADC evaluation may be adopted here to calculate the effective resolution of our look-up-table. For an N bits ADC, ENOB is defined as:

$$\mathrm{ENOB}=N-\frac{1}{2}\log_2((\sigma_{\mathrm{e}}{}^2+\sigma_{\mathrm{q}}{}^2)/\sigma_{\mathrm{q}}{}^2) \tag{11}$$

where $\sigma_{\mathrm{q}}{}^2$ is the quantization noise while $\sigma_{\mathrm{e}}{}^2$ represents other noises. As for TOT technique, $\sigma_{\mathrm{q}}{}^2$ is the quantization noise brought in by the discontinuity of our look-up-table, and σ_{e} becomes σ_{em}, the RMS of time width of the smallest signal. From Eq.(11) we get the definition of Effective Number of Bits for TOT technique:

$$\mathrm{ENOB_{TOT}}=N-\log_2(\sqrt{\sigma_{\mathrm{q}}{}^2+\sigma_{\mathrm{em}}{}^2}/\sigma_{\mathrm{q}}) \tag{12}$$

For an N bits uniform quantization look-up-table (time width to slew correction value, $T\Rightarrow t$) within range $[0,T_{\mathrm{M}}]$, $\sigma_{\mathrm{q}}=T_{\mathrm{M}}/(\sqrt{12}\times 2^N)$. Eq. (12) expands to:

$$\mathrm{ENOB_{TOT}}= N-$$

$$\log_2(\sqrt{\sigma_{\mathrm{Tt}}{}^2+(T_{\mathrm{M}}/(\sqrt{12}\times 2^N))^2}\times\sqrt{12}\times 2^N/T_{\mathrm{M}}) \tag{13}$$

In our test σ_{em} is 28.53ps. Time width of the largest input amplitude (-2000mV) can be taken as T_{M}, which is 42.08ns. If we make a 10 bits look-up-table, an $\mathrm{ENOB_{TOT}}$=8.62 will be obtained. That means our T(time width) correction is equal to the $T(A)$ correction performed by an ADC with ENOB=8.62. The worst effective resolution of our slew correction is Δt_{eM}=5000ps/$2^{8.62}$=12.71ps. For large signals, the effective resolution is much better. Better effective resolution can also be achieved by increasing the quantization bits of time width. If the quantization bits of the look-up-table is 11, then we get an $\mathrm{ENOB_{TOT}}$=8.70. The cost is that the complexity of establishing and employing the look-up-table will increase.

5 Conclusions

In practical applications, the TOT circuit before HPTDC may be designed into a small board which could be placed at the front end closely to PMT tubes. Differential output of the TOT board will be transmitted out from the detector to HPTDC board for time measurement. This is more tolerable to noise and attenuation than the traditional way of transferring analog signal. By the way, it is more favorable if the TOT board is designed into an ASIC which will consume less power.

For all the above we have presented the feasibility of applying TOT technique to PMT signals processing, which would bring in much more effective and economical time measurement Front End Electronics design. The evaluation result of our test has met the requirement of TOF(time of flight) system at

BESIII[7]. But because of the exponential integration circuit, the relationship between time width and slew correction is very complex. We need to establish the look-up-table for each TOT board. The calibration procedure may be accomplished off line by software or implemented on line by FPGA on the HTPDC board. The other consideration is that the time width would vary with the shape of PMT pulses. Further study has been undertaken on this issue. Despite of these intrinsic drawbacks, the TOT technique presented in this paper is applicable for most PMT signals processing.

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