# Design and implementation of the constant fraction discriminator for glass MRPC timing

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## Abstract

The analog front-end electronics based on the constant fraction discrimination method is designed and optimized for the Multigap Resistive Plate Chamber (MRPC) timing measurements. The total time resolution of  $\sim 40$  ps has been obtained for 10 and 12 gaps MRPCs using cosmic setup and a muon beam at the IHEP U-70 accelerator in Protvino, which complies with the conditions of the SPD experiment at NICA.

Keywords:

MRPC, constant fraction discriminator, time resolution

## 1. Introduction

High energy and heavy ion experiments require good particle identification based on the time-of-flight (TOF) techniques. MRPCs are widely used in large area TOF systems due to its good time resolution, high detection efficiency and relatively low cost production. In particular, MRPCs are used for particle identification at ALICE [1, 2, 3], HARP [4], STAR [5], PHENIX [6], BM@N [7, 8] and other experiments.

The Spin Physics Detector [9] is a universal facility for studying the nucleon spin structure and other spin related phenomena with polarized proton and deuteron beams placed at the second interaction point at NICA [10]. The SPD TOF system will also be based on MRPCs. The purpose of the MRPC system is to make a  $3\sigma$  separation of  $\pi/K$  and K/p in the momentum range up to few GeV/c. The required time resolution of the SPD MRPC

system is  $\sim 60$  ps [9].

Typically, the total time resolution of MRPC systems achieved in present experiments is  $50 \div 70$  ps. The best time resolution of ~20 ps has been obtained for an MRPC having 24 gas gaps with a width of 160  $\mu$ m built of thin 400  $\mu$ m "soda-lime" glass sheets after the correction for the time slewing [11]. The time resolution of an MRPC is mainly determined by the detector intrinsic resolution, which depends on the design and physics of the gas discharge; the jitter of the front-end electronics (FEE) and cables; and the time-to-digit converter (TDC) channel uncertainty.

Improvement of the MRPC time resolution requires correction for the time slewing, which arises from the signal time delay dependence on its amplitude. Therefore, the time of the leading edge has to be corrected for the signal amplitude. Nowadays, the MRPC signal amplitude is usually estimated using the fast Time-Over-Threshold (ToT) method, which only reads out the threshold crossing time and the signal time interval over the threshold. FEE based on NINO ASIC with an embedded ToT function [12, 13] and TDC system built using the HPTDC ASIC [14] can provide contribution to the total time resolution of  $\sim 20$  ps [11]. Another way is to analyze the MRPC signal waveform. In particular, the NA61 MRPC system [15, 16] is based on the use of a fast analog amplifier and DRS4 module [17] for the signal waveform analysis. The time resolution of the fast analog FEE and high-speed DRS4 based [18] waveform digitization module, integrating the waveform correction and filtering, digital discrimination and linear interpolation is better than 10 ps [19]. A new analysis method based on a neural network and machine learning algorithms was proposed and implemented to make the best use of the MRPC signal waveform [20, 21]. The MRPC time resolution obtained by this method using 7 points on the signal leading edge was found better than provided by the traditional ToT [21].

The constant fraction discrimination method [22] is widely used for TOF measurements [23]. The fast discriminator which triggers at a constant fraction of the input signal amplitude allows to obtain the optimum time resolution regardless of the signal amplitude. In this case there is no need for the time slewing effect correction. Moreover, a constant fraction discriminator (CFD) is suitable for large scale systems due to its simplicity and low cost.

This paper presents first results on the design, optimization and first application of the FEE based on the constant fraction discrimination method for the SPD MRPC system [9]. The paper is organized as follow. Section 2 describes the MRPC design used for the studies and analysis of their signal shapes. The constant fraction discriminator concept and schematics is discussed in Section 3. The results of the cosmic muons and muon beam test at the U70 accelerator are described in Section 4 and Section 5, respectively. The conclusions are drawn in the last Secton.

## 2. MRPC

Four MRPCs were manufactured for the present studies. The two studied MRPCs have 10 and 12 gas gaps in total, while two others used for the trigger purpose have 10 gas gaps. Each MRPC consists of two identical 5- or 6-gap stacks with an anode strip readout plate in between. The schematic cross section of a 10-gap MRPC is shown in Fig.1.



Figure 1: The schematic view of a 10-gap MRPC.

Each gas gap is formed by two 0.55 mm thick glass plates with a bulk resistivity of  $3 \times 10^{13}$   $\Omega$ cm. The gap between the glass plates is defined by a spacer made of fishing line 250  $\mu$ m in diameter. Graphite conductive coating with a surface resistivity of 2–5 M $\Omega$ /square is painted on outer surfaces of the stacks to distribute high voltage to create an electric field in the sensitive area. The anode readout plate is a one-sided PCB with a thickness of 100  $\mu$ m. The thickness of the copper coating is 35  $\mu$ m. The sensitive area of the MRPC is  $16 \times 35.1 \text{ cm}^2$ . The MRPC has  $32 \ 10 \times 160 \text{ mm}^2$  readout strips with 1 mm gaps between them. The signals are read on both ends of the anode strips. Each MRPC is enclosed in a gas-tight aluminium box. The bottom of the box is made of a double-sided PCB (motherboard) with a thickness of 2.5 mm. The top of the box is covered by an aluminium plate 1.5 mm thick. The MRPCs were operated at a high voltage across the gap up to 3 kV with ~50 cc/min flow of 90% C<sub>2</sub>F<sub>4</sub>H<sub>2</sub>, 5% SF<sub>6</sub> and 5% C<sub>4</sub>H<sub>10</sub> gas mixture.

The simulation based on the simple Townsend model [24] of gas discharge shows that the intrinsic time resolution of an MRPC with 10 gas gaps of 250  $\mu$ m thickness each is ~20 ps [25].



Figure 2: Averaged signals from the 12-gap and 10-gap MRPCs shown by the squares and circles, respectively (left panel). The signal amplitudes from the 12-gap MRPC (right panel).

The MRPC signal shape was studied with cosmic muons. For this purpose, the two studied and two trigger MRPCs were stacked vertically on the top of each other. The MRPCs were operated at a high voltage across the gap of 3 kV. The coincidences of the signals from the two outer chambers were used as a trigger for the Tektronix DPO4104B oscilloscope (bandwidth 1 GHz, 5 GS/sec), while the waveforms of the signals from both ends of the central strips of the two inner chambers were recorded by the LabView program. The results of the measurements for 100 triggers are presented in Fig.2. The left panel demonstrates the averaged waveforms of the signals for

the 12-gap (MRPC1) and 10-gap (MRPC2) MRPCs shown by the squares and circles, respectively. The observed signal reflections are due to mismatch of the anode strip line impedance (~65  $\Omega$ ) and 50  $\Omega$  termination of the oscilloscope input. The right panel of Fig.2 represents the distribution of the signal amplitudes from the 12-gap MRPC. The discrimination threshold was set to 0.9 mV while only signals with amplitude above 2 mV were selected for the analysis.

The waveforms shown in Fig.2 were used to reconstruct the MRPC original signal shape. The oscilloscope and MRPC contributions were taken as a single pole and a triangular (linear rise and linear fall) shape, respectively. Best fit gives the rise and fall times as 416 ps and 509 ps, respectively, with a 160 ps time constant for a single pole corresponding to the oscilloscope bandwidth of 1 GHz.

#### 3. FEE concept and schematics

CFDs are widely used for time measurements [22, 23]. Its conceptual diagram is shown in Fig.3. The incoming signal is split in two identical copies: one is delayed, and another one is inverted and attenuated by a defined factor. Difference of the two signals has zero-crossing point independent on the signal amplitude, thus suppressing the time slewing, present in simple leading-edge discriminators. Timing is then determined with a zero-cross circuit which is usually a Schmitt-trigger with the lower threshold set to zero. In present study an alternative method explained in the right panel of Fig.3 is used. Instead of zero-crossing point finding, two leading edge comparators with two thresholds marked in the plot as  $V_1$  and  $V_2$  are used. The linear combination of the corresponding time points,  $T_1$  and  $T_2$ , is used to reconstruct the signal time reference.

This combination might be, e.g., an extrapolation to zero threshold emulating a conventional CFD, or it can be optimized for best time resolution. One of the thresholds can have a negative value, however, the thresholds with both positive values were used in the present design. The advantage of this method is a flexibility in optimization of the time resolution, important at the R&D stage. The obvious disadvantage is the doubling of TDC channels.

The zero-crossing time  $T_0$  can be calculated (assuming the linear signal rise and negligible electronics noise) as

$$T_0 = \frac{V_2 \cdot T_1 - V_1 \cdot T_2}{V_2 - V_1} = T_1 - Q \cdot |T_2 - T_1|, \tag{1}$$



Figure 3: Conceptual diagram of a CFD (left panel) and zero-crossing point finding for two positive thresholds (right panel).

where Q=1/(R-1) and  $R=V_2/V_1>1$ . Time  $T_0$  depends linearly on the  $(T_2-T_1)$  difference. The case of the nonlinear  $T_0$  dependence which provides a better time resolution is described in Section 5.



Figure 4: Schematic diagram of a two-cascade wide-bandwidth amplifier.

A simplified schematics of a two-cascade amplifier is shown in Fig.4. The discrimination threshold must be in the range of  $\sim 0.5$  mV of the MRPC signal to obtain high detection efficiency. Since fast comparators are typically stable with thresholds down to about 10 mV, the MRPC signal must be amplified by a factor of  $\sim 20$ . The fast AD8099 amplifier [26] which has a unity gain bandwidth up to 3 GHz was selected for the first cascades. It has an overall

DC gain of 19 (being  $50-\Omega$  loaded) and rise time of 1.1 ns measured and confirmed with LTspise simulations [27]. The optimal delay of the CFD for this circuit is estimated as 0.55 ns.

The CFD delay/attenuation cascade was also designed using the AD8099 amplifier[26]. The delay was implemented with a piece of 50- $\Omega$  coaxial cable. It will be replaced by a 50- $\Omega$  PCB trace in the final design. The comparator cascade was built using an ultra-high speed MAX9601 comparator [28] which had two channels, used for low- and high thresholds. Both CFD and comparator cascades are shown in the left and right panels of Fig. 5. The thresholds  $V_1$  and  $V_2$  were set to ~0.4 mV and ~0.8 mV of the amplifier input (MRPC output) signal.



Figure 5: CFD circuit with delay/attenuation functions (left), the comparator cascade (right).

The intrinsic time resolution of the readout chain was measured with triangular input pulse shape (rise and fall edges of 500 ps) taken from a pulse generator. The signal was split by a passive high frequency divider and sent to different CFD amplifier board channels. The time difference between two channels was measured with TDC64VHLE time-to-digit converter (TDC) module [29] based on HPTDC ASIC running in 25-ps binning mode with an intrinsic resolution of ~17 ps. The signal amplitude after the divider was varied from 2.8 to 34 mV.

The time difference  $T_2$ - $T_1$  for two TDC [29] channels as a function of the generator signal amplitude is shown in the left panel of Fig.6. Measured points shown by the solid squares and circles were approximated by the



Figure 6: Left: time difference  $T_2$ - $T_1$  for two TDC [29] channels shown by the solid symbols with the approximation by the inversed amplitude function given by the solid line. Right: time resolution for the  $T_1$  signal, the line is the results of the approximation by the function (2).

inversed amplitude function (solid line) as expected for the linear rising edge. However, it was found that an offset of 1.9 mV must be introduced for better approximation. Some offset is expected for the MAX9601 comparator circuit [28]. The time resolution as a function of the generator signal amplitude was estimated from the time difference  $T_1(\text{Ch.7})$ - $T_1(\text{Ch.3})$  for two different FEE channels using two TDC [29] channels. The resulting time resolution was obtained dividing the RMS value by  $\sqrt{2}$  (assuming TDC channels were identical). The result is shown in the right panel of Fig.6 together with the best fit of the data by the resolution function taken in the following form

$$RMS = C_0 \bigoplus \frac{C_1}{\sqrt{A}} \bigoplus \frac{C_2}{A},\tag{2}$$

where A is the signal amplitude in mV,  $C_0$ ,  $C_1$  and  $C_2$  are the constant, jitter and noise term contributions, respectively. The constant term  $C_0$  is consistent with the expected TDC resolution of ~17 ps. The intrinsic resolution is dominated by the TDC contribution  $C_0$  for the signal amplitudes above 10 mV. The resolution for signals with smaller amplitudes is dominated by the electronics jitter  $C_1$  and noise  $C_2$  terms.

## 4. MRPC test with cosmic muons

The readout chain was tested and optimized with detecting cosmic particles. The setup is shown in Fig. 7. It consists of four MRPCs, three scintillator counters and a block of lead to filter out low-energy particles. The two inner MRPCs were used for the signal measurements, while the two outer chambers were included in the trigger logics similar to the MRPC signal shape measurements described in Section 2. The distance between the MR-PCs was 48 mm. The chambers were aligned horizontally with an accuracy of  $\pm 0.3$  mm. The scintillation counters had  $18 \times 18$  cm<sup>2</sup> active area covering the full length of the chamber strips. The lead block had the thickness of 9 cm absorbing muons with a kinetic energy below ~200 MeV ( $\beta$ >0.94). Therefore, the time of flight between the two studied MRPCs varied as low as  $\sim 10$  ps for these particles providing negligible contribution to the total time resolution. The trigger was formed as a coincidence of signals from the three scintillation counters and 1 strip of each of the trigger MRPCs. The trigger rate was about 0.05 Hz. Measurements were performed with a full readout chain described in Section 3.





Figure 7: Scheme and picture of the cosmic test setup.

The detection efficiency  $\epsilon$  of the 12-gap MRPC as a function of the applied high voltage is shown in Fig.8. The CFD thresholds were set to  $V_1 = 0.45$ mV and  $V_2 = 0.85$  mV. The efficiency was defined as a ratio of the numbers of the signals with the amplitudes above the low threshold  $V_1$  (solid circles)



Figure 8: Efficiency of the 12-gap MRPC. Solid circles and squares are the results for low and high thresholds, respectively.

or high threshold  $V_2$  (solid squares) to the number of triggers. It was found  $\sim 96\%$  for chamber bias above 2.8 kV.

The time resolution was measured with HV bias of 2.85 kV with a CFD fraction fixed to 0.5. The time reference  $T_0$  was calculated for each MRPC according to an iterative algorithm described in [7]. The time difference  $T_0$  for the two MRPCs under test is presented in Fig.9. The line is the result of the approximation by a gaussian function. The time resolution of the standalone MRPC was obtained by dividing the obtained standard deviation from the gaussian fit by  $\sqrt{2}$  (assuming both MRPCs contribute identically).

The time resolution of a single MRPC is shown in Fig.10 as a function of the CFD delay varied from 0.45 ns to 0.65 ns. The solid triangles and circles represent the results for the time differences of the low threshold comparator  $T_1$  and zero crossing  $T_0$ , respectively. Best  $T_0$  time resolution of 42 ps was achieved with a 0.55 ns delay, as expected from the MRPC pulse shape measurements. Note that the difference between the low threshold  $(T_1)$  and zero crossing  $(T_0)$  time resolutions was negligible at the optimal CFD delay of 0.55 ns.



Figure 9: MRPC  $T_0$  time resolution.

Figure 10: CFD delay optimization.

### 5. Muon beam test

The MRPC test setup is schematically shown in Fig. 11. The data were taken using a muon beam at the U-70 accelerator in Protvino [30]. The muons were originated from the interaction of the circulating proton beam with the internal target placed in the accelerator vacuum chamber. The duration of the beam spill was about 0.3 s with a repetition rate of 0.1 Hz. No momentum selection was applied to the beam. The averaged momentum of muons was about 2 GeV/c. The beam intensity was  $100 \div 10 \text{k muons/s/cm}^2$ in the test area. The setup consists of four scintillation counters (S1-S4), two trigger MRPCs and two MRPCs under test. Small-size counters S1, S2formed an active beam area of  $1 \times 1$  cm<sup>2</sup>. The signals from the trigger MRPCs were included in trigger logics, as described in previous sections. They also were used to align the detectors on the beam axis. The low and high CFD thresholds were increased up to  $V_1 = 0.8$  mV and  $V_2 = 1.4$  mV, respectively, to reduce possible noise contribution. The CFD delay was set initially to 0.55 ns according to the results of the measurements with cosmic muons. The MRPC efficiency was measured to be 99% at HV bias above 2.75 kV.

The correlation of the  $T_1$  and  $T_2 - T_1$  differences for the two MRPCs under test is demonstrated in the left panel of Fig.12. The line is the result of simple linear correction according to (1) with the factor Q = 1/(R-1) = 1.33 (for



Figure 11: Schematic view of the MRPC test setup. S1-S4 are the scintillation counters, the test and trigger MRPCs are the chambers under test and included in the trigger.



Figure 12: Left: correlation of  $T_1$  versus  $T_2$ - $T_1$ , right:  $T_0$  time difference for the MRPCs under test calculated according to (1).

set thresholds). One can see good agreement of the  $T_1$  and  $T_2 - T_1$  data correlation with the linear approximation (1). The  $T_0$  distribution for the two MRPCs is shown in the right panel of Fig.12 together with the gaussian approximation result. The RMS from the data and standard deviation from the gaussian fit are ~71 ps and ~64 ps, respectively.



Figure 13: Left: Optimization of the correction factor Q, right:  $T_0$  time difference at Q=0.7.

Linear correction for  $T_0$  according to (1) is valid only in the absence of electronics noise. However, its contribution is non negligible as one can see from the left panel of Fig.6. The  $T_0$  distribution was analyzed for different values of the correction factor Q varied in the range from -1 up to +2. The values Q=-1 and Q=0 corresponded to  $T_0=T_2$  and  $T_0=T_1$ , respectively. The result is presented in the left panel of Fig.13. Both minimal values of the RMS from the data and standard deviation from the fit are reached at  $Q \approx 1.16$ and  $Q \approx 0.7$ , respectively. The  $T_0$  distribution for the correction factor Q =0.7 is shown in the right panel of Fig.13. In this case the RMS from the data and standard deviation from the fit are  $\sim 74$  ps and  $\sim 59$  ps, respectively.

In general, signal rise is nonlinear (see Fig.2), thus the  $T_2$ - $T_1$  difference can be nonlinear. In this case the expression for the  $T_0$  value (1) can be rewritten in a more general form:

$$T_0 = T_1 - C(T_2 - T_1), (3)$$



Figure 14: Left: correlation of  $T_1$  versus  $T_2$ - $T_1$  with the correction function  $C(T_2 - T_1)$ , right:  $T_0$  time difference for the MRPCs under test calculated according (3).

where  $C(T_2 - T_1)$  is a correction function that minimizes the  $T_0$  dispersion (either RMS from the data or standard deviation from the fit) for the given data set. This function can be found with the iterative algorithm described in Ref.[7]. The  $C(T_2 - T_1)$  function for the data set used for Fig.12 is shown by the solid points in left panel of Fig.14. One can see that  $C(T_2 - T_1)$  is almost linear for the  $T_1$ - $(T_2$ - $T_1)$  correlation center while some non-linearity appears only for the distribution tails.  $C(T_2 - T_1)$  was parameterized by polynomials for further practical use. The resulting  $T_0$  distribution for the two MRPCs calculated using expression (3) is shown in the right panel of Fig.14 together with the gaussian approximation result. The RMS from the data and standard deviation from the fit are  $\sim 67$  ps and  $\sim 60$  ps, respectively. The standard deviation value is almost the same as in the case of optimized linear correction (see right panel of Fig.13) because  $C(T_2 - T_1)$  is practically linear in the area of main peak. The RMS value for the data is smaller than in the case of optimized linear correction. Therefore, the data obtained with the muon beam were analyzed using a nonlinear algorithm.

The resulting time resolution of a single MRPC was estimated by dividing the  $T_0$  standard deviation by  $\sqrt{2}$ , assuming the two chambers contribute identically. Fig.15 shows the time resolution when bias of one chamber was fixed while that of the second chamber was varied. It was found that the



Figure 15: MRPC time resolution as a function of HV setting.

Figure 16: MRPC time resolution as a function of CFD delay.

optimal HV bias is 2.85 kV for both chambers. However, only weak HV dependence of the time resolution was observed over the full MRPCs working range.

The effect of CFD delay on time resolution is demonstrated in Fig.16. This measurement was made with a fixed 0.55 ns delay for the 10-gap MRPC CFD by varying the delay for the 12-gap chamber CFD. As expected, it was found that the optimal CFD delay for both chambers is 0.55 ns as already determined in the cosmic test.

## 6. Conclusions

The CFD discriminator for MRPC readout is designed and implemented. the intrinsic time resolution of the readout chain measured with a waveform generator is 15-30 ps for input amplitudes of 3-30 mV.

The CFD concept is validated for 10- and 12- gap MRPCs with cosmic muons and with a 2 GeV/c muon beam. The MRPC total time resolution achieved with optimized CFD parameters (thresholds and delay time) is ~40 ps being consistent with the results obtained using time reconstruction methods based on neural networks and ToT correction [21].

Further improvement of the CFD discriminator for MRPC readout can be

related to use of faster amplifiers with lower power consumption. In future, the CFD concept can be implemented in a new front-end ASIC for MRPC similar to VFAT3 ASIC [31] developed for GEM detectors.

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