Detailed study on the intrinsic time resolution of the future MRPC detector

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Abstract

Recent large physics experiments have proposed a higher requirement of 20 ps for the time resolution of Multi-gap Resistive Plate Chambers(MRPCs). In order to meet this requirement, one should have a deeper understanding of the detector physics and the factors that bring the time resolution. A series of fundamental studies on the intrinsic time resolution of the MRPC detectors are presented in this paper. The sources of the timing uncertainties, their influences and the relationship with the detector geometry are analyzed. Different reconstruction methods are also implemented and the intrinsic time resolution for different detectors is presented. These results are not only instructive for the design of MRPC detectors with 20 ps time resolution, but also provide useful reference for the research on future detectors.

1 Introduction

The Multi-gap Resistive Plate Chambers(MRPC) is a gaseous detector with very high time resolution and rate capability. It has been widely used in many large physics experiments as the main components of the Time-of-Flight(ToF) system. The time resolution of the present MRPCs used in these experiments is in the range of 60\textendash80 ps \cite{1–3}. However, in the future Solenoidal Large Intensity Device(SoLID) at Jefferson Lab(JLab), the requirement for the time resolution becomes very strict, which is only around 20 ps \cite{4} so as to achieve a $3\sigma$ separation of $\pi/K$ up to the momentum of 7GeV/c. This is challenging for both the detectors and the readout electronics. In order to verify the achievability of this goal, a very detailed study of the intrinsic time resolution of MRPCs is needed before the design and construction.

MRPC originates from the Resistive Plate Chamber(RPC) and their working mechanism is very similar. Previous studies of the intrinsic time resolution is mainly based on the RPC detectors, especially for the cases when signals start from only 1 single electron \cite{5}. This

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model can approximately explain the performance of the RPC detector which only has 1 or 2 gas gaps and works at relatively low electric field, but it is far from satisfactory for the MRPC. A typical structure of the MRPC usually has much thinner (100∼200 µm) and more gas gaps (usually more than 5, while some are even more than 20 [6]). So in MRPC, signals induced by multiple avalanches from different gas gaps are dominant, which is significantly different from the widely used ”single” electron model. It is this kind of structure that makes MRPC enjoy a much better timing ability compared to RPCs. There are also some studies that extend the RPC geometry to the multi-gap style [7], but the gas gap in these work is still very large and as a consequence, the working electric field is limited.

This work presents a detailed study of the intrinsic time resolution of MRPC detectors mainly from three aspects: the sources of the timing uncertainties in terms of the detector physics, their quantitative contributions to the final resolution, and the influence of reconstruction algorithms. The traditional reconstruction algorithm is called the Time-over-Threshold (ToT), which sets a threshold to the induced signal and discriminates the crossing time. Since almost all the previous results of the detector are analyzed with this method, some theoretical derivations based on ToT are presented in this paper. From these derivations, sources of the uncertainties are extracted and their quantitative contributions to the time resolution are analyzed by simulation. The resolution with respect to some geometry factors is also reported, which provides important information for the design of future MRPC detectors.

Recently, a new algorithm based on several sets of neural networks is proposed [8] to further improve the detector resolution. Theoretical analysis of the network is quite difficult but the intrinsic performance of this method can be estimated and explained by the simulation, which is also included in this paper.

The paper is organized as follows: Sec.2 describes the theoretical derivations of the intrinsic time resolution for MRPCs analyzed with the ToT method. Sec.3 presents the sources of the time uncertainties and their quantitative values for several typical MRPCs. Sec.4 shows the resolution with respect to some important geometry factors. Sec.5 describes the intrinsic time resolution obtained with neural network. Finally Sec.6 concludes this paper.

2 Theoretical analysis of intrinsic time resolution with ToT method

When particles impinge on the MRPC detector, they will interact with the working gas and the ionized electron-ion pairs are created. The electrons will immediately drift toward the anode and trigger avalanche multiplication under the electric field. According to the Townsend effect, in the avalanche, the number of electrons grows approximatively in an exponential way. However considering randomness, uncertainty exists around the exponential multiplication. Suppose there is an electron created at position $z = 0$ and drift along the $z$ axis under the
electric field. The probability for it to become \( n \) electrons at position \( z \) is \( P(n, z) \) [5]:

\[
P(n, z) = \frac{1 - k}{\bar{n}(z)} e^{(k-1)\frac{m}{\bar{n}(z)}} = \frac{1}{A'_{av}} e^{-\frac{A'}{A'_{av}}}
\]

where \( A'_{av} = \frac{\bar{n}(z)}{1 - k} \)

\( \bar{n}(z) \) is the mean value of the number of electrons at \( z \), and \( k \) is the ratio \( \eta/\alpha \), where \( \alpha \) is the first towsend coefficient and \( \eta \) is the attachment coefficient. This equation is obtained under the assumption that \( z \) is the position where \( \bar{n}(z) \) is sufficiently large. It shows that the number of electrons and thus the amplitude of the signal \( A' \) at a specific position (or after some specific drifting time) also follows an exponential distribution with a mean value of \( A'_{av} \), and this uncertainty only comes from the avalanche itself. According to the Ramo theory, the induced current of \( m \) primary electrons is:

\[
i = \sum_{i=j}^{m} A_j e^x = \left[ \sum_{i=j}^{m} A_j \right] e^x = B e^x
\]

\[
B = \sum_{i=j}^{m} A_j, \ x = \alpha' vt
\]

where \( \alpha' = \alpha - \eta \) is the first effective towsend coefficient. \( A_j \) is the amplitude of signal caused by only 1 single electron and it follows an exponential distribution shown in Eq.1:

\[
f(A_j) = \frac{1}{A_{av}} e^{-\frac{A_j}{A_{av}}}
\]

The probability distribution function (PDF) of variable B can be obtained using \( f(A_j) \), which is:

\[
f(B) = f(A_1) \otimes f(A_2) \ldots \otimes f(A_m) = \frac{B^{m-1} e^{-\frac{B}{A_{av}}}}{(m-1)! A_{av}^m}
\]

the symbol \( \otimes \) denotes the **Fourier convolution**, which can be described as:

\[
f(x) \otimes g(x) = \int f(x - \tau) g(\tau) d\tau
\]

If a fixed threshold \( B_{th} \) is set to the current \( i \) in Eq.2, then \( x \), which is related with the threshold crossing time \( t \) is:

\[
x = \ln\left( \frac{B_{th}}{B} \right), \quad B = B_{th} e^{-x}
\]

Then the PDF of \( x \) can be obtained with \( f(B) \) and \( B(x) \) (Eq.6):

\[
g(x) = f(B(x)) \left| \frac{dB}{dx} \right| = \frac{r^m}{(m-1)!} \exp[-r e^{-x} - mx] \quad \text{where,} \ r = \frac{B_{th}}{A_{av}}
\]

The standard deviation of \( g(x) \) is the intrinsic time resolution in unit of \( 1/\alpha' v \) for signals starting from \( m \) primary electrons. Fig.1a shows this resolution with respect to the threshold.
Different curves are from different $m$. The standard deviation of $x$ is independent of the threshold when it is reasonably large, which is at the scales around tens of femto coulomb proved by the simulation. This is resulted from the property of function $g(x)$. Fig.1b shows that the time resolution improves with the number of primary electrons $m$, because the superposition of multiple avalanche averages the signals and therefore makes the waveform more uniform.

However, in the real MRPC detectors $m$ is not a constant but itself a random variable. The uncertainty of $m$ mainly comes from the primary energy deposited and the position distribution of the collisions. It is really hard to summarize an analytical expression of the probability distribution function of $m$, let alone the combination of $m$ and $x$. In this situation, the monte carlo simulation of the MRPCs is an effective way and it is described in Sec.3.

3 Different sources that contribute to the intrinsic time resolution

To achieve the goal of a time resolution at the scale of 20 ps, it is not only important to know the values of the intrinsic resolution, but also the sources it comes from, because this would help us better design the structure of MRPC detector. Since only the intrinsic resolution is considered in this paper, the variance brought by the read out electronics and noise is neglected. So according to Eq.7 and its characteristics, the time resolution of the MRPC is attributed to 3 main origins:
Table 1: The geometry and working condition of several typical MRPC detectors.

1. uncertainty of the position where primary interactions take place.
2. uncertainty of the energy deposited and the number of ionized electrons created.
3. uncertainty of the avalanche multiplication.

This is studied by a monte carlo simulation of the detector, which utilizes the simulation framework built by our group [9]. This framework consists of several modules, each dealing with one relatively independent part of the simulation. So it is very easy to separate the influence of every source apart and analyze its own contribution. In this section, some typical MRPCs that are used in several high energy physics experiments including ALICE [1], CBM [2], STAR [3] and BESIII [10] are explored. RefMRPC, a very thin-gap detector [6] and 2 prototypes assembled in our laboratory [8] are also included. Tab.1 shows the geometry and the working electric field of these MRPCs and Fig.2 shows the quantitative contributions from the sources mentioned above. The electric field in the gas gap is set with the value shown in Tab.1, which is nearly the same as the working field given in the references of the corresponding experiments.

In Fig.2, ”Position Uncertainty” considers only the uncertainty of the interaction position, while the energy deposited in every collision is kepted the same and all the avalanches strictly obey the exponential growth. In this situation, the intrinsic time resolution of all the MRPCs in Tab.1 is on the order of 10 ps, and does not vary much among different detectors. The subtle difference should come from the variance of $m (Var(m))$ and the random errors. $m$, defined in Sec.2, is actually the number of electrons that develop into effective avalanche. Higher electric field leads to a much more intense multiplication, so ionized electrons created in most area of the gap can grow into large signals. This means the distribution of the position has very little effects on $Var(m)$. However, when decreasing the electric field, only electrons that are very close to the cathode are able to contribute to $m$. Then $m$ will largely depend on the distribution of the position, and therefore $Var(m)$ is larger. That’s why the resolution of RefMRPC and THU1 is better. Meanwhile, the time resolution benefits from more gas gaps. The interactions and multiplications happened in different gaps are independent, so the sum of signals from multiple gaps is more uniform and has smaller variance. This explains why the STAR MRPC has larger time resolution than CBM, though the electric field is higher.

"Position+Energy Uncertainty" in Fig.2 shows the results when uncertainty from deposited energy is added to ”Position Uncertainty”. In this case, the number of the primary
electrons has a much larger variance, making some of the ionized clusters contain large amounts of electrons (large clusters), while some only a few (small clusters). This worsens the time resolution. It can be clearly seen from Fig. 2 that this effect is obvious in thick-gap detectors, but not so obvious in thin-gap ones. It is essentially due to the electric field, which is relatively low in thick-gap MRPCs in order to avoid streamers. The reason is similar to the "Position Uncertainty". In the condition of low electric field, the uncertainty for the small clusters to be effective is very large, depending much on the position. The multiplication of large clusters in the same event will finally be restricted by the space charge effects and will not be able to compensate for the loss of the small ones. Thus the variation of the signal amplitude and the time resolution is large. However when the electric field becomes higher, the possibility for clusters to become effective is much larger, even in the cases of small clusters. The variation of the amplitude is hardly affected by the energy fluctuation. That is why RefMRPC and THU1 is much better than the others.

"Position+Energy+Avalanche Uncertainty" considers also the variance of avalanche. The time resolution brought by the avalanche can be explained by Fig. 1. Longer track implies a much larger m, while higher electric field guarantees a larger effective Townsend coefficient α′ (1/α′v is the unit of time resolution). Both of these 2 factors indicate a better resolution. The results shown in Fig. 2 are consistent with the theory, but obviously, uncertainty of avalanche is small and does not vary much from detectors to detectors. This is because though m is uncertain for all the MRPCs in Tab. 1, it is absolutely a number larger than 15. In Fig. 1b, this is the value where the resolution is already small and decreases slower.

In general, longer track and higher electric field are two key factors that bring a good time resolution. This fundamental knowledge about the intrinsic resolution is indeed important to understand the performance of the MRPC detector, but when it comes to the design and construction, these two factors are always determined by the geometry.

Figure 2: The contribution to the time resolution from different sources for several typical MRPCs.
Figure 3: The time resolution of MRPCs with different detector geometry. (a) The thickness of the gas gap and the number of gaps. (b) The number of stacks in a detector.

4 The geometry affecting the intrinsic time resolution

The structure of the detector geometry has a significant impact on MRPC’s performance. As mentioned above, MRPCs used in most present physics experiments have a time resolution around 60 ps. This is because the gap thickness is all around 220−250 μm. According to Fig. 2, the 20 ps timing requirement of SoLID experiment makes the design of thin gaps to be the only promising choice. This section shows the quantitative results of the intrinsic time resolution of MRPC with different geometry, aiming to provide guidance for designing the detectors.

Fig. 3a shows the time resolution with respect to the gap thickness and the number of gaps. To control the final avalanche size and avoid streamers, the effective Townsend coefficient times the gap thickness are fixed at $\alpha'g = 28$, which is close to a normal working condition of the MRPCs shown in Sec. 3. Thinner and more gaps clearly have a better time resolution. Besides, if the electronics noise is concerned, thin-gap detectors will show greater advantages because the leading edge of their waveform is steeper. Another interesting point is that when the number of gaps goes from 6 to 12, the time resolution drops significantly, but it remains almost unchanged when the number of gaps is over 20. This corresponds to Fig. 1b, where the derivative of $\sigma$ with respect to $m$ is a decreasing function. Based on Fig. 3a and considering the goal of 20 ps, the possible choices for next generation MRPCs are only the designs with thickness below 160 μm, because the intrinsic resolution of the detector should be at least below 15 ps in order to leave some room for the electronics.

The curves with larger number of gaps in Fig. 3a give a much better result than smaller ones, but in actual cases, the voltage needed by these detectors is much higher and hard to realize if all the gaps are in one single stack. Usually, gaps are divided into several stacks.
and the voltage is added separately on each stack. However, when the detector is divided into more stacks, it will become much thicker, because inserting PCB layers for voltage also means inserting more glasses. This will lead to a larger variance of the starting time for each avalanche, and thus results in a larger time resolution, which is shown in Fig.3b by the solid curves. All the data points in this plot are MRPCs with 32 gas gaps and the dashed curves are the time resolution if the arrival time at each stack is corrected to be the same. In this "corrected" case, the resolution improves with respect to the number of stacks, because the starting time of each avalanche is limited inside only one stack, and the stack will become thinner when its number is increased. The rules are the same for three kinds of the gap thickness in the figure and so are all the other choice of thickness.

5 The intrinsic time resolution analyzed with neural network

In the previous sections, the intrinsic time resolution either obtained by theoretical derivations or by monte carlo simulations has a same assumption — the time reconstruction algorithm is the so-called ToT method. This is a traditional method and used nearly in all the present experiments. However, if this assumption is changed and another algorithm is applied, the intrinsic time resolution could be completely different. This section compares the results from ToT and neural networks.

![Figure 4: The comparison of the intrinsic time resolution analyzed with two different algorithms.](image)

MRPCs with 12 gas gaps and different gap thickness are simulated and analyzed. Same as Sec.4, the $\alpha'g$ is fixed at 28. Fig.4 shows the results obtained with the ToT and LSTM. LSTM is short for the Long Short Term network which is a special case of the Recurrent Neural Network(RNN). By analyzing all the data of the waveform, LSTM finds a very
good connection between the signal and particles arrival time. The intrinsic time resolution becomes better. Details of implementation and the main idea of this network can be found in [8]. The result is reasonable, because algorithmically, ToT is just one specific model, it is designed by the scientists and is proved to be useful. But neural networks, no matter what network specifically, can be recognized as a set of models. The goal of network training is merely to find a model in the model set that solves the problem best, which means this new algorithm is more comprehensive and thus more powerful. The theoretical understanding of the intrinsic resolution of this algorithm should be similar to the ToT, but with different equations.

6 Conclusions

A detailed study of the intrinsic time resolution for future MRPC detectors is presented in this paper. Theoretical derivations of the intrinsic time resolution for MRPC signals are described. Based on the theory and a monte carlo simulation, the sources of the timing uncertainty and the effects brought by the detector geometry are carefully analyzed. Finally, the intrinsic resolution obtained with another reconstruction algorithm — the neural network is studied and the results are shown to be much better than the traditional ToT method. This paper proves that the goal of the 20 ps MRPC is achievable from the intrinsic point of view, and provides useful guidance on how to design the real detector. Meanwhile, the intrinsic time resolution summarized in this work also provides useful reference for all the other groups working on MRPC detectors.

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