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A novel method of encoded multiplexing readout for micro-pattern gas detectors*

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Abstract: The requirement of a large number of electronic channels poses a big challenge to the further applications of Micro-pattern Gas Detectors (MPGDs). By using the redundancy that at least two neighboring strips record the signal of a particle, a novel method of encoded multiplexing readout for MPGDs is presented in this paper. The method offers a feasible and easily-extensible way of encoding and decoding, and can significantly reduce the number of readout channels. A verification test was carried out on a 5 cm×5 cm Thick Gas Electron Multiplier (THGEM) detector using a 8 keV Cu X-ray source with 100 μm slit, where 166 strips were read out by 21 encoded readout channels. The test results show good linearity in its position response, and the spatial resolution root-mean-square (RMS) of the test system is about 260 μm. This method has potential to build large area detectors and can be easily adapted to other detectors similar to MPGDs.

Keywords: micro-pattern gas detector, encoded multiplexing, readout method, position measurement

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1 Introduction

Advances in microelectronics and printed circuit board (PCB) techniques during the past few decades have triggered a major transition in the field of gas detectors, from wire chambers to MPGDs. Due to their good spatial resolution, high rate capability, large active areas, and radiation hardness, MPGDs such as the Gas Electron Multiplier (GEM) [1], the Thick GEM (THGEM) [2] and the Micromegas [3] are widely used in high-energy physics, and have also opened a new trend in fundamental science, medical imaging and industry [4]. MPGDs need high-density narrow anode readout elements to achieve good spatial resolution. Most of the readout techniques employ a large number of electronic channels to read out directly. The large number of readout channels has become an issue for most experiments using MPGDs. Consequently, some alternative readout techniques have been employed to reduce the number of electronic channels, such as resistive interpolating readout [5, 6], and delay-line readout [7, 8].

By using the redundancy that each particle usually showers the signal on several neighboring strips in MPGDs, an encoded multiplexing readout technique was developed by S. Procureur et al at Saclay, France [9], which innovatively reduces the number of readout channels, but the encoding method is complicated and the encoding sequences need to be reordered. A novel method of encoded multiplexing readout is presented in this paper which offers a simple and easily-extensible way of encoding, and it is feasible to decode the hit position where a signal is shared on k neighboring strips, $k\geqslant 2$. This method can dramatically reduce the number of readout channels, and it has been successfully tested with a 5×5 cm^2 THGEM [10] where 166 strips are read out by 21 encoded readout channels.

2 Principle and method

2.1 Principle

The development of MPGDs with large areas and high spatial resolution requires a large number of readouts. However, for a particular event, the signal is usually localized on a few related electronic channels, the others being void, especially in low incident flux experiments. The features of signal sparsity and electronics redundancy can be used to track the particles with an

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appropriate encoded multiplexing pattern, which could greatly reduce the number of electronics channels.

Because of charge transverse diffusion, a particle signal's cluster is almost always distributed on at least two neighboring strips in MPGDs. This feature can be utilized to track particles with an appropriate encoded multiplexing construction {strips}→{channels}, as shown in Fig. 1(a), where XY represents the each encoded multiplexing connection, X is the channel number and Y is the strip number. All the channel numbers X could form an encoding list by the sequence of the connected strip numbers (Y). Supposed that two neighboring strips i and $i+1$ are connected to two given channels a and b, and the two channels are also connected to several other non-neighboring strips. If a signal is recorded only on channels a and b, it is almost certain that the hit position is in the strips i and $i+1$, since there is only one doublet combination of a and b in the encoding list. In other words, if any doublet combination of channel numbers appears at most once in the encoding list, the hit position of signal can be precisely tracked by the case of two neighboring fired strips.

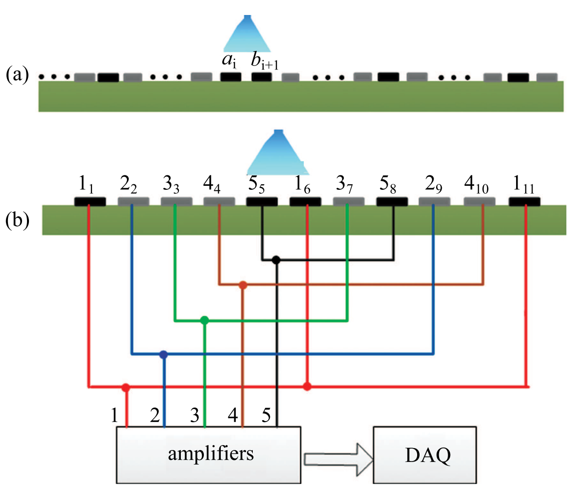

Fig. 1. (color online) Principle of the encoded multiplexing method.

A specific example is shown in Fig. 1(b), where 11 strips are read out by 5 readout channels. All the C_5^2 doublet combinations of 5 channels, corresponding to the 11 strips, appear once in the encoding list {1,2,3,4,5,1,3,5,2,4,1} where each two neighboring numbers form a combination. If a particle event hits two neighboring strips 5 and 6, this results in the signal being recorded on its encoded channel 5 and 1. In turn, the combination of fired channel 5 and 1 can uniquely decode the hit position strip 5 and 6. As given in the decoding table of 5 channels shown in Table 1, the combination of two fired channels can uniquely decode the two hit strips of the particle in the detectors.

Table 1. Decoding table of 5 readout channels.

X: fired channels	1,2	2,3	3,4	4,5	5,1	1,3	3,5	5,2	2,4	4,1
Y: hit strips	1,2	2,3	3,4	4,5	5,6	6,7	7,8	8,9	9,10	10,11

Similarly, if all the C_n^2 doublets combinations of n channels are constructed to a feasible encoding list in an appropriate way, C_n^2 doublets two neighboring strips can be uniquely decoded. It means that n channels can read out by a theoretical maximum of $C_n^2{+}1$ strips, as $C_n^2{+}1$ strips contain two neighboring strips for each of C_n^2 doublets. Generally, the principle described above is a graph theory problem of whether there is an Euler walk to construct a path which uses each edge exactly once, where the edges represent the doublet combinations and the vertices represent the readout channels. Figure 2 shows an Euler walk of 5 readout channels, corresponding with the encoding list {1,2,3,4,5,1,3,5,2,4,1} of Fig. 1(b). According to Euler's path theorem [11], it can be proved that there is an Euler walk when the numbers of readout channels n is an odd number, as all of its vertices have an even degree. In other words, n channels can construct a maximum encoding list of $C_n^2{+}1$ strips when n is an odd number, and each doublet combination occurs exactly once in the list. It turns out that there are more than one constructions of Euler walk, such as 5 channels having the other encoding lists {1,2,3,1,4,2,5,3,4,5,1} and {1,3,5,2,4,1,2,3,4,5,1}.

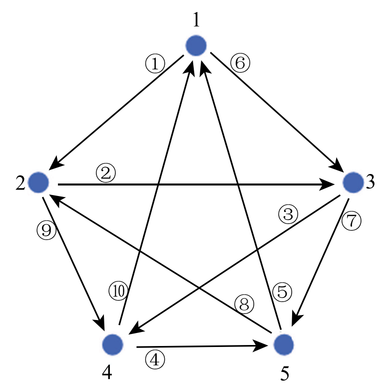

Fig. 2. (color online) An Euler walk of 5 readout channels.

2.2 Encoding

In practice, it must be considered that a detector may record a signal on more than two neighboring strips while the previous discussion is based on the assumption of only two neighboring fired strips. It triggers the question of k-uplets ($k>2$) repetition which may lead to incorrect decoding. As seen in Fig. 1, when a signal is recorded on the channel 2, 3, 4, 5, it is not sure whether the hit position is in $\{2_2,3_3,4_4,5_5\}$ or $\{3_7,5_8,2_9,4_{10}\}$. An alternative solution is to choose an optimized encoded multiplexing connection with appropriate constraints so as to minimize the deviation of the hit position.

Table 2. The encoding list of multiplexing connections for $2k+1$ readout channels.

row	list of encoded multiplexing connections
1	1_1, 2_2, 3_3
2	1_4, 4_5, 2_6, 5_7, 3_8, 4_9, 5_{10}
3	1_{11}, 6_{12}, 2_{13}, 7_{14}, 3_{15}, 6_{16}, 4_{17}, 7_{18}, 5_{19}, 6_{20}, 7_{21}
.	……
k	$1_{C^2_{2k-1}+1}$, $(2k)_{C^2_{2k-1}+2}$, $2_{C^2_{2k-1}+3}$, $(2k+1)_{C^2_{2k-1}+4}$, $3_{C^2_{2k-1}+5}$, …… $(2k-1)_{C^2_{2k+1}-2}$, $(2k)_{C^2_{2k+1}-1}$, $(2k+1)_{C^2_{2k+1}}$ $1_{C^2_{2k+1}+1}$

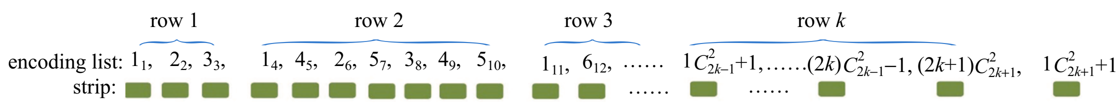

Fig. 3. (color online) The corresponding relation between the encoding list and strips.

To obtain an available encoding list for the general case that a signal is recorded on k neighboring strips, $k \geqslant 2$, encoding constraints and rules are made as follows: (1), use an odd number of electronics channels to encode readout. (2), any doublet combination of channel numbers appears exactly once in the whole list, and they can be constructed as an Euler walk. (3), the encoded connections are listed by row, and a new row is added to the list when two new channels are added. (4), for the k-row, the k-list is the newly added connections by channel $2k$ and $2k+1$, where $2k$ and $2k+1$ are interleaved in 1, 2, 3 $\cdots$. $2k-1$ then form the k-row list 1, $2k$, 2, $2k+1$, 3, $2k, \cdots, 2k-1$, $2k$, $2k+1$.

The encoding list of multiplexing connections constructed by the above rules is shown in Table 2. The form XY represents each multiplexing connection, where X is the channel number and Y is the strip number along the detector. For $2k+1$ readout channels, the encoding list consists of k rows, corresponding with strips as shown in Fig. 3.

2.3 Decoding

In the above construction, the designed encoding list is robust to decode the hit position when two channels are fired. For a given doublet of two fired readout channels (a,b), the larger number can fix the row position so that the exact fired strip can be decoded with another channel number. For example, the doublet of channels (7, 5) can be uniquely decoded to the strips (18, 19) in Table 2.

What is important is to verify the feasibility of decoding the general case of k neighboring fired strips, $k>2$. By using the encoding rules and encoding list in Table 2, it can be analyzed as follows: when k=3, most of the positions can be uniquely decoded except the end of each row. For example, the fired channel group {5, 6, 7} is decoded to the hit position range $\{7_{18}, 5_{19}, 6_{20}, 7_{21}\}$, which results in 1 strip uncertainty. But it is explicit that there is no repetition of 3-uplets of 5, 6, 7 at other positions. Similarly, it turns out there will be less than 2 strips uncertainty of hit range caused by the multiplexing decoding when k neighboring fired strips, $k>3$, but this will not lead to an incorrect decoding.

When a signal records on k channels, $k>2$, it can be decoded by ordering the number of the fired channels based on the encoding list. For instance, the fired channel group {1, 2, 3, 6, 7} is decoded to the hit range $\{1_{11}, 6_{12}, 2_{13}, 7_{14}, 3_{15}, 6_{16}\}$ with 1 strip uncertainty. In addition, the uncertainty can be diminished by the center method and center of gravity method.

Besides, the front rows of encoding list are constructed with a small number of readout channels because the list is added with every two new channels, which will leads to a large uncertainty. For instance, the fired channel group {1, 2, 3, 4, 5, 6, 7} will be decoded to the hit range from strip 1 to strip 21 with 10 strips uncertainty. So the first few rows can be discarded to diminish the uncertainty for a larger number k of neighboring fired strips. For example, when we discard the first three rows and the encoding list starts from the fourth row, this list can decode precisely in the case of at most 16 neighboring fired strips.

3 Verification test

3.1 Design of anode readout PCB

In order to verify this method, an encoded multiplexing anode readout PCB was manufactured and equipped for a THGEM detector with 5 cm×5 cm. The anode readout PCB has 166 one-dimensional strips of 152 μm width and 304 μm pitch. As discussed previously, the first four rows of the encoding list are discarded in this design so as to decode the case of at most 20 neighboring fired strips. Theoretically, this should be more than enough for almost all signals of the detector. Therefore, the 166 strips need 21 channels for encoded multiplexing readout. The encoding list starts from (1,10 $\cdots$) of the fifth row and ends at ($\cdots$ 20,16) of the tenth row, as shown in Table 3. Each strip is connected to the corresponding channel based on the encoding list. Figure 4 shows the corresponding routing between the strips and the readout channels on the PCB layout. According to the encoding rules and list, the hit strip can be decoded by the fired channels.

3.2 Experimental setup and results

As shown in Fig. 5, a verification test was carried out on the THGEM detector using a 8 keV Cu X-ray source and Ar/iC_4H_10 (97:3) gas mixture. The detector was biased to a total gain of 1×10^4. A slit about 100 μm width in a thin brass sheet was used to produce a miniaturized X-ray beam. A manual movable platform was used for the position scanning test.

Table 3. The encoding list of 166 strips readout by 21 channels for 5 cm×5 cm THGEM.

row	list of encoded multiplexing connections
5	1_1, 10_2, 2_3, 11_4, 3_5, 10_6, 4_7, 11_8, 5_9, 10_{10}, 6_{11}, 11_{12}, 7_{13}, 10_{14}, 8_{15}, 11_{16}, 9_{17}, 10_{18}, 11_{19}
6	1_{20}, 12_{21}, 2_{22}, 13_{23}, 3_{24}, 12_{25}, 4_{26}, 13_{27}, 5_{28}, …, 8_{34}, 13_{35}, 9_{36}, 12_{37}, 10_{38}, 13_{39}, 11_{40}, 12_{41}, 13_{42}
7	1_{43}, 14_{44}, 2_{45}, 15_{46}, 3_{47}, 14_{48}, 4_{49}, 15_{50}, 5_{51}, ……,10_{61}, 15_{62}, 11_{63}, 14_{64}, 12_{65}, 15_{66}, 13_{67}, 14_{68}, 15_{69}
8	1_{70}, 16_{71}, 2_{72}, 17_{73}, 3_{74}, 16_{75}, 4_{76}, 17_{77}, …………,12_{92}, 17_{93}, 13_{94}, 16_{95}, 14_{96}, 17_{97}, 15_{98}, 16_{99}, 17_{100}
9	1_{101}, 18_{102}, 2_{103}, 19_{104}, 3_{105}, 18_{106}, 4_{107}, ……………,19_{128}, 15_{129}, 18_{130}, 16_{131}, 19_{132}, 17_{133}, 18_{134}, 19_{135}
10	1_{136}, 20_{137}, 2_{138}, 21_{139}, 3_{140}, 20_{141}, 4_{142}, …………,21_{163}, 15_{164}, 20_{165}, 16_{166}

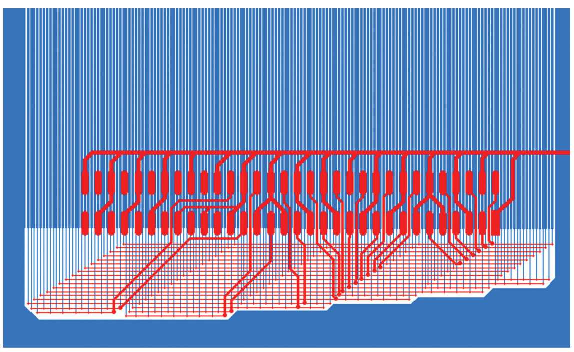

Fig. 4. (color online) Scheme of the PCB connections between the 166 strips and 21 channels.

Signals from 21 multiplexed channels were digitized by a GASTONE chip [12], then readout by a Xilinx development board to process and analyze. GASTONE is a 64-channel digital-output ASIC designed to readout the GEM Inner Tracker detector of the K Long Experiment (KLOE). Each channel is made of a charge sensitive preamplifier, a shaper, a discriminator and a monostable module. Digital output data are transmitted via serial interface at 100 Mbit/s data rate, so the electronics can respond to a high event rate.

With proper grounding and shielding, the threshold of the GASTONE chip was set down to 100 mV in this test, corresponding to 5 fC. A cluster size histogram before the decoding procedure was tested and is shown in Fig. 6. It shows that more than 86% of events hit at least 2 strips, and they can be tracked precisely on the detector. About 14% of event hits cannot be decoded, as they only have 1 strip cluster size. Moderating the drift electric field, avalanche electric field, THGEM hole size and using low-noise electronics can spread the cluster size, thus more events hit at least 2 strips and can be tracked. Besides, reducing the strip widths can also lead to more events hitting at least 2 strips.

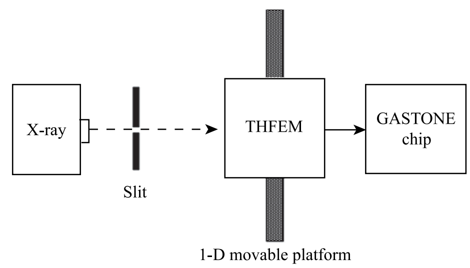

Fig. 5. Experimental setup of the verification test.

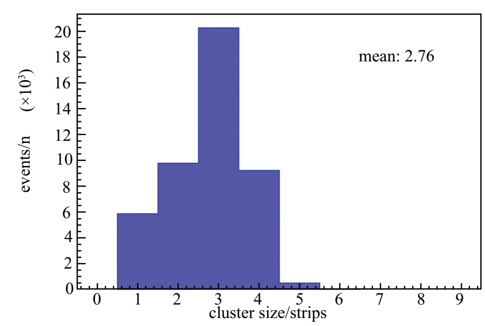

Fig. 6. (color online) Cluster size histogram of the signals.

The GASTONE is a digital output chip and cannot be used to measure the charge value, so the center method is implemented in the decoding procedure. Figure 7 shows the decoded result for a signal hit in the position of mean strip 43.47 with RMS of 0.85 strip, matching with the fact that X-ray beam spot was over the upper part of detector. During the position scanning test, the detector was moved with a step size of 0.2 mm in a 10 mm range. Figure 8 shows the summary of the decoded position for the X-ray scan across the readout strip. There are some points off the line near strip 40, because the encoding list of strips (39,40,41,42) corresponds to the channels (13,11,12,13) at the end of the sixth row. As discussed above, it will result in at most 1 strip uncertainty. The uncertainty can be corrected in the analog-output front-end electronics by finding the largest signal set of consecutive fired channels in the encoding list. The test results indicate that the method can correctly decode the hit position, and has good linearity in the postion scanning test. The spatial resolution RMS of the test system is about 260 μm (0.85 pitch), including the contributions of X-ray source, detector and noise.

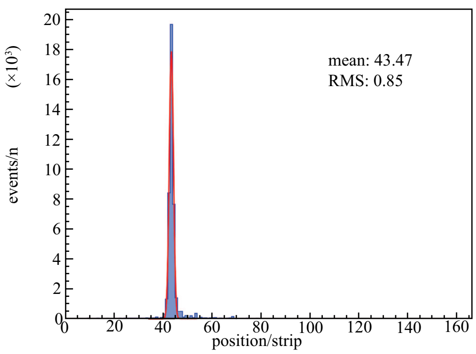

Fig. 7. (color online) Position resolution measured for the upper part of the detector.

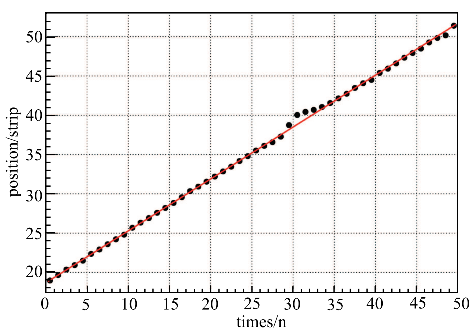

Fig. 8. (color online) Decoded results of position scanning test.

4 Discussion and conclusion

The method easily extends to two-dimensional tracking. For example, using two-dimensional orthogonal strip readout as a charge collection electrode [13], the horizontal strips and the vertical strips are encoded for multiplexing readout, respectively. By comparison with conventional direct pixel readout [14] which can resolve multiple events in coincidence, the encoded multiplexing readout is limited to single events within the acquisition window, which depends on the dead time of the electronics. Unlike the direct pixel readout, this method cannot handle the case of high incident flux, but should still have comparable performance at 10 kHz/cm^2 as using the similar method [9]. In reality, the dead time of the electronics is the biggest bottleneck for high rate capability MPGDs. Significantly, the method has a great advantage in that it can reduce the number of readout channels. The method can read out strips by n readout channels while conventional direct readout [15] needs C_n^2 channels. For a large 50 cm×50 cm GEM detector with 0.5 mm pitch one-dimensional strips readout, conventional direct readout needs 1000 readout channels, but this encoded method only needs about 50 readout channels.

A novel method of encoded multiplexing readout for micro-pattern gas detectors is presented in this work. This method is systematic and easily extensible, offering a general way of encoding and decoding. The method is verified by a test of a 5 cm×5 cm THGEM detector equipped with the encoded anode readout PCB, where 166 strips are read out by 21 encoded readout channels. The test results show its general properties and performance under operation with 8 keV X-rays with a 100 μm slit. It has good linearity in its position reponse, and the spatial resolution RMS of the test system is about 260 μm.

Although it is based on the redundancy that at least two neighboring strips record the signal of a particle, with robust detectors such as MPGDs and low-noise electronics, it is still an attractive prospect for building large area detectors and has a wide range of applications in and beyond particle physics. Moreover, it can also be used for other detectors similar to MPGDs, such as drift chambers and scintillators.

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References

1 F. Sauli, Nucl. Instrum. Methods A, **386**: 531 (1997)
2 A. Breskin et al, Nucl. Instrum. Methods A, **598**: 107 (2009)
3 Y. Giomataris, Nucl. Instrum. Methods A, **376**: 29 (1996)
4 M. Titov et al, Nucl. Instrum. Methods A, **581**: 25 (2007)
5 G. Guedes et al, Nucl. Instrum. Methods A, **513**: 473 (2003)
6 H. Wagner et al, Nucl. Instrum. Methods A, **523**: 287 (2004)
7 M.Y. Dong et al, Chinese Physics C, **37**(2): 026002 (2013)
8 Y. Zhou et al, Nucl. Instrum. Methods A, **604**: 71 (2009)
9 S. Procureur et al, Nucl. Instrum. Methods A, **729**: 888 (2013)
10 Q. Liu et al, Journal of Instrumentation, **8**(11): C11008 (2013)
11 J. Gross et al, *Graph theory and its applications*, CRC press, 2005
12 A. Balla et al, Nucl. Instrum. Methods A, **604**: 23 (2009)
13 S. Chernenko et al, Journal of Instrumentation, **9**(09): C09026 (2014)
14 D. Neyret et al, Journal of Instrumentation, **4**(12): P12004 (2009)
15 A. Bressan et al, Nucl. Instrum. Methods. A, **425**: 254 (1999)