An X-ray imaging device based on a GEM detector with delay-line readout *

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Abstract An X-ray imaging device based on a triple-GEM (Gas Electron Multiplier) detector, a fast delay-line circuit with 700 MHz cut-off frequency and two dimensional readout strips with 150 μm width on the top and 250 μm width on the bottom, is designed and tested. The localization information is derived from the propagation time of the induced signals on the readout strips. This device has a good spatial resolution of 150 μm and works stably at an intensity of 10^5 Hz/mm^2 with 8 keV X-rays.

Key words delay-line readout, gas electron multiplier (GEM), X-ray imaging

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1 Introduction

Recently, many laboratories have been involved in research into Gas Electron Multiplier (GEM) based detectors for high resolution particle tracking and X-ray imaging applications [1–3]. By applying suitable potentials on the GEM electrodes, the effective gain of a single layer GEM foil is at a magnitude of 10^2 and that of a triple layer GEM detector can reach more than 10^5. Unlike the detectors which consist of wire electrodes (e.g. MWPC), its micro-cell structure endows the GEM detector with very good time responses and high counting abilities. The GEM limits the avalanche process within its holes and separates the avalanches from electron-ion collection, so that the space charge effect is greatly decreased. A GEM equipped with a micro-strip readout electrode and using the Center-of-Gravity (COG) method can reach a spatial resolution of less than 100 μm. Large area GEM detectors have been designed for tracking intense particle beams and for X-ray imaging [4–6]. Most of the readout techniques employ large numbers of electronics. For example, a GEM detector with an effective area of 50 mm × 50 mm requires readout electronics of at least 2×100 channels for the COG method, containing the amplifiers, shapings, ADCs, and trigger logics in each channel. That is very expensive. A possible solution, widely used on wire chambers, is the delay-line readout method which can convert the position information of the avalanche processes into time differences. A two-dimension position encoding delay-line readout needs four electronics channels. Unlike the wire-roll delay-line employed for wire chambers, the delay-line designed for the GEM detector requires a faster response and better accuracy when working in intense particle flux and high spatial resolution conditions.

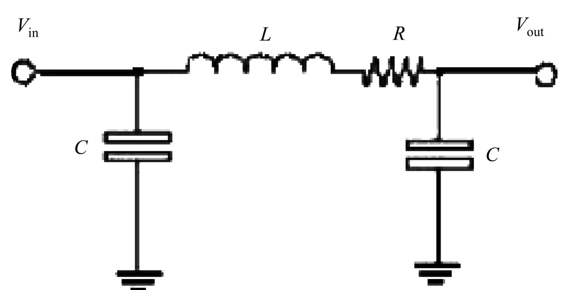

Fig. 1. One delay-line cell (L: inductor, C: capacitor, R: internal resistance of the inductor).

Based on the structure of the GEM readout electrode and the principles of the delay-line circuit, a lumped delay-line model is developed [7, 8]. This fast delay-line consists of many discrete LC (inductor-capacitor) cells, as shown schematically in Fig. 1.

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Each discrete LC cell is connected to an individual anode or cathode strip. The localization information is derived from the propagation time of the induced signals which travel along the delay-line and are exported to current amplifiers at each end of the delay-line. The linearity and time response of the delay-line depend on the per-cell time delay and the distributed parameters of the PCB route.

2 Design of the delay-line circuit

The three significant parameters in the design of delay-line circuit are the per-cell time delay τ, the cut off frequency ω_0 and the characteristic impedance Z_0. These parameters can be calculated with the following formulas,

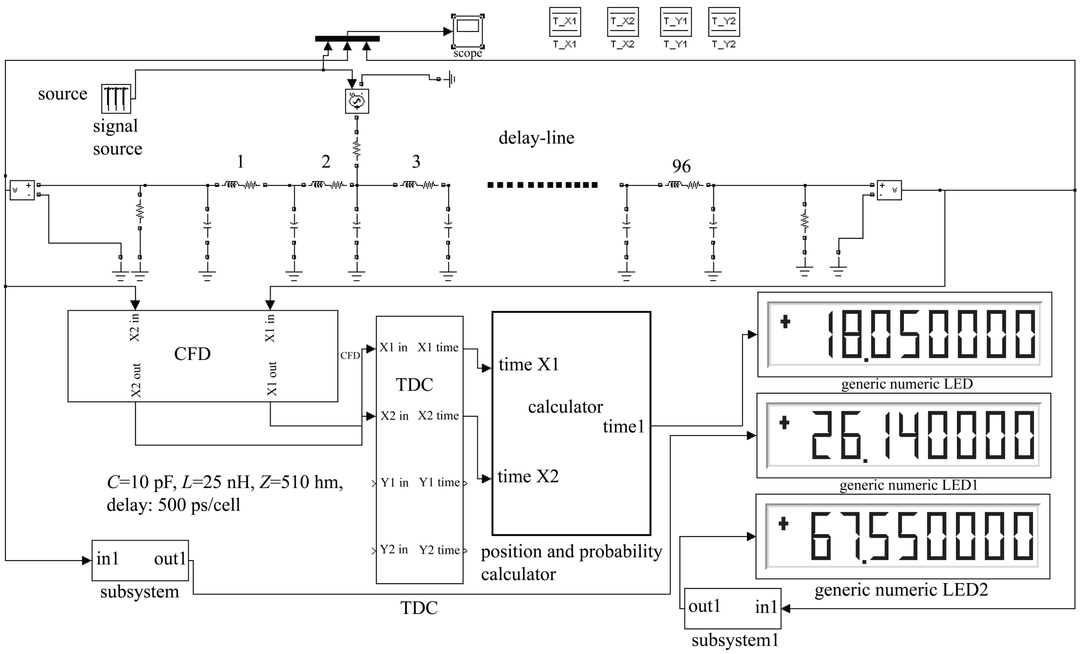

Fig. 2. The simulation model of the delay-line readout system.

$$\omega_0 \approx \frac{1}{\sqrt{LC}}, \quad Z_0 = \frac{1}{\sqrt{1-\left(\frac{\omega}{\omega_0}\right)^2}}\sqrt{\frac{L}{C}} \approx \sqrt{\frac{L}{C}} \; (\omega \ll \omega_0),$$

$$\tau = \frac{1}{\omega}\left[\frac{\omega}{\omega_0} + \frac{1}{3}\left(\frac{\omega}{\omega_0}\right)^3 + \cdots\right] \approx \sqrt{LC} \quad (\omega \ll \omega_0). \tag{1}$$

We designed a delay-line PCB with 96 LC cells and chose $L = 290$ nH, $C = 7$ pF, the cut-off frequency $\omega_0 = 700$ MHz and the characteristic impedance $Z_0 = 207\ \Omega$. According to the electro circuit model of the delay-line PCB, a full simulation model of the delay-line readout system is constructed in the Matlab-Simulink [9] environment, as shown in Fig. 2. It consists of the delay-line, the amplifier, the Constant Fraction Discriminator (CFD) and the Time-to-Digital Converter (TDC). A typical signal of a GEM detector, a trapeziform pulse with 40 ns width, 3 ns rising time and 0.75 V amplitude, is injected into the delay-line at a certain cell port and divided into two parts, propagating forward and backward along the delay-line. The output signals from both ends of the delay-line are discriminated by the CFD and digitally transformed with the TDC. Fig. 3 shows the shape of the input signal and the output signals. The simulated delay time is 1.42 ns/cell.

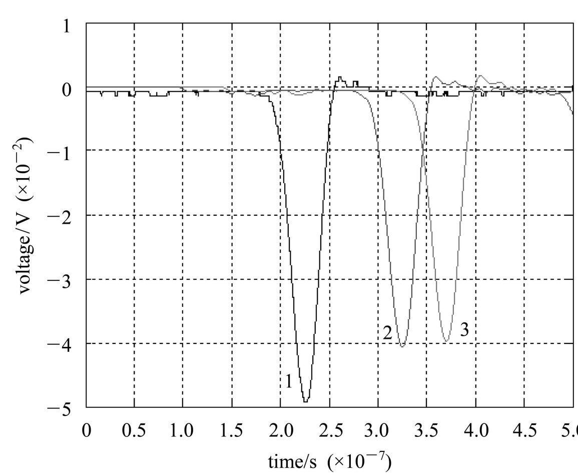

Fig. 3. The simulated input signal (1) and output signals (2, 3).

Figure 4 shows the output signals at both ends of the delay line with tested signal at the 32nd input port (1.6 ns rise/fall time, 20 ns width and 100 mV amplitude). Fig. 5 shows photographs of the delay-line PCB.

Due to the influence of distributing parameters of the readout strips, the calibrated results are 5.05 ns/cell on the top side and 5.24 ns/cell on the bottom side when the delay-line is connected to readout PCBs which have two orthogonal sets of parallel strips with 400 μm pitch, 150 μm width on the top plane and 250 μm width on the bottom plane. The relationship between time difference and input position can be written as (Fig. 6),

$$\begin{aligned} X &= 0.20\times T+48.48,\ \text{Top Strip} \\ Y &= 0.19\times T+48.20,\ \text{Bottom Strip} \end{aligned} \tag{2}$$

where X and Y are the positions of input signals and T is the time difference of the output signals from the corresponding delay-line PCB.

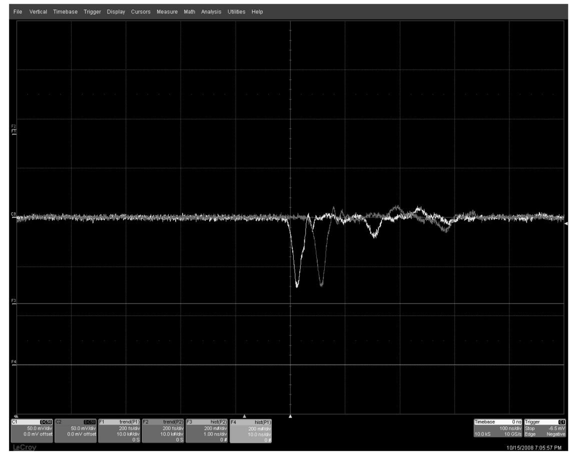

Fig. 4. The output signals at both ends of the delay-line.

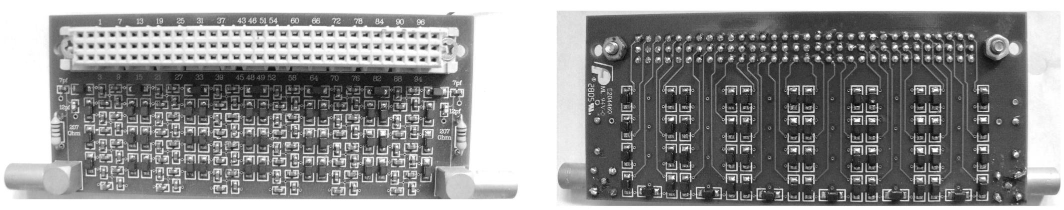

Fig. 5. Photographs of the delay-line PCB of 96 cells.

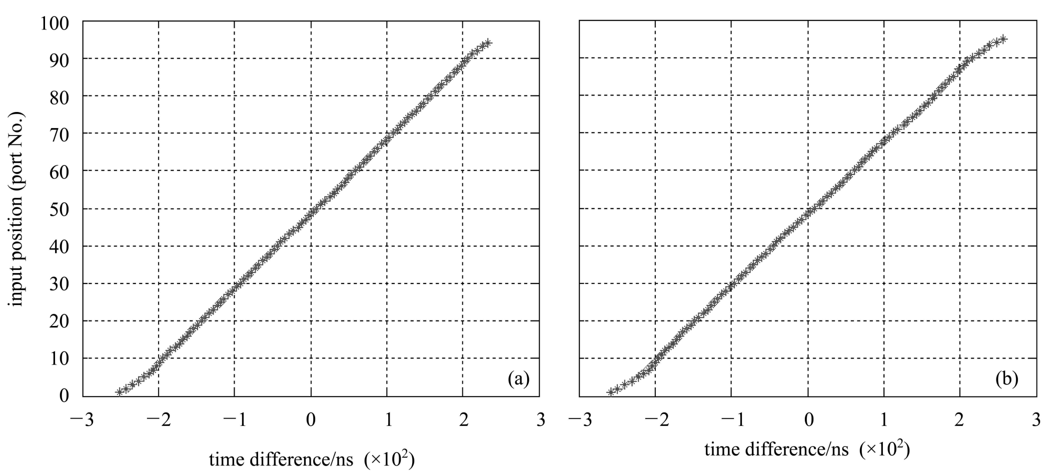

Fig. 6. The calibration results of the top strip plane (a) and the bottom strip plane (b).

3 The setup and test results

A GEM detector with a 50 mm × 50 mm sensitive area and delay-line readout electronics (Fig. 7, Fig. 8) is set up and tested with 8 keV X-rays. An aluminium block with 0.2 mm slot width is used as the collimator. The output signals of the GEM detector are amplified by a current amplifier (1 ns rise time) and the distribution of the time difference of output signals

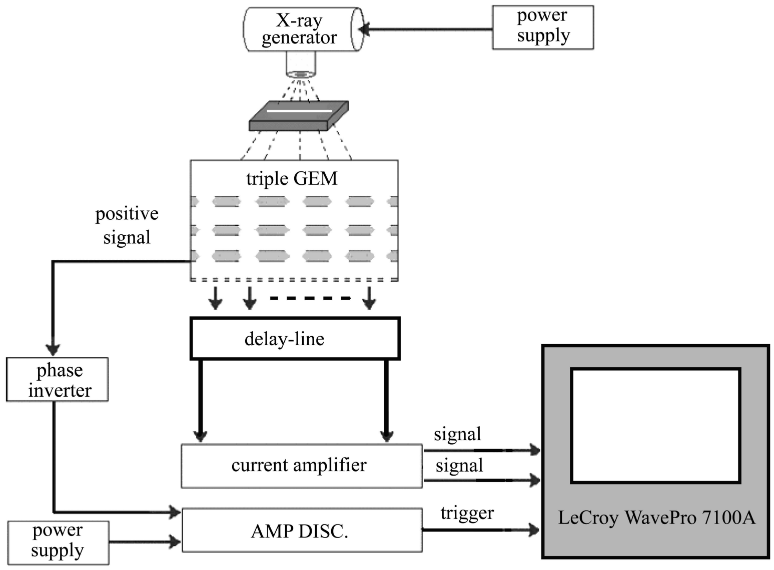

Fig. 7. The setup of GEM X-ray imaging with delay-line readout.

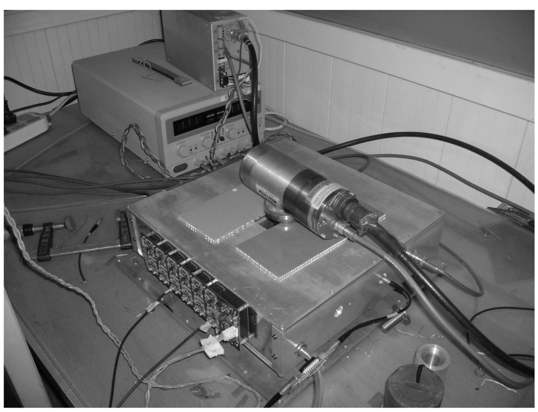

Fig. 8. Photograph of the GEM X-ray imaging device.

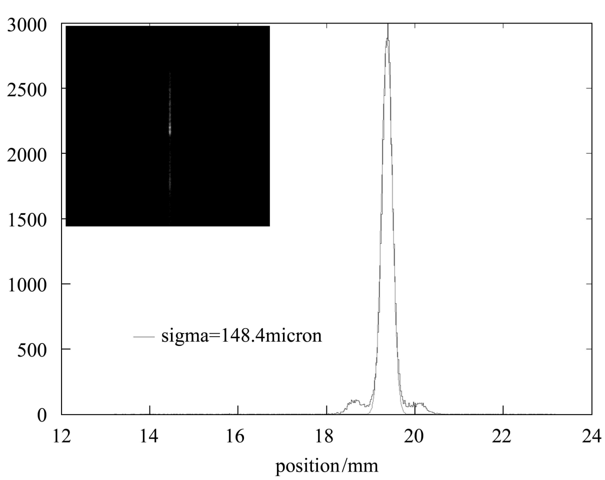

Fig. 9. Position resolution measured for the top strip plane ($\sigma_x = 148$ μm).

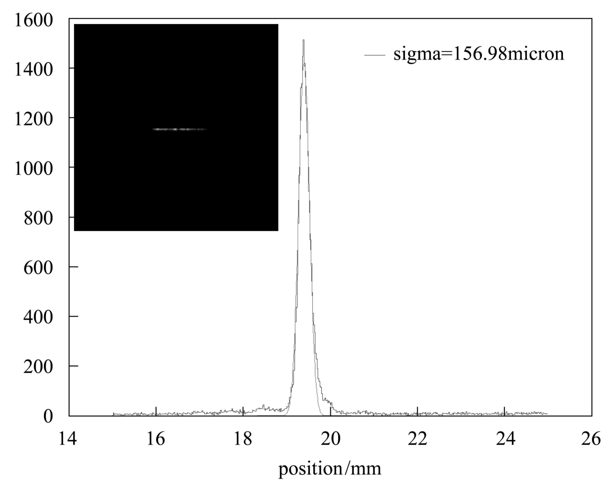

Fig. 10. Position resolution measured for the bottom strip plane ($\sigma_y = 157$ μm).

can be measured directly by an oscilloscope (LeCroy WavePro 7100 A). Imaging of the slot is obtained, as shown in Fig. 9 and Fig. 10. The spatial resolutions (σ) are $\sigma_x = 148$ μm and $\sigma_y = 157$ μm, which include the contribution from the readout electronics. When the intensity of X-rays varies from 10^3 Hz/mm^2 to 10^5 Hz/mm^2 [10], the fluctuation of position resolution is about ± 6 μm [11]. Fig. 11(a) is a double-slot image tested with 0.8 mm pitch and 0.2 mm width and Fig. 11(b) shows the imaging of the capital letter "U", both tested at 10^5 Hz/mm^2 intensity.

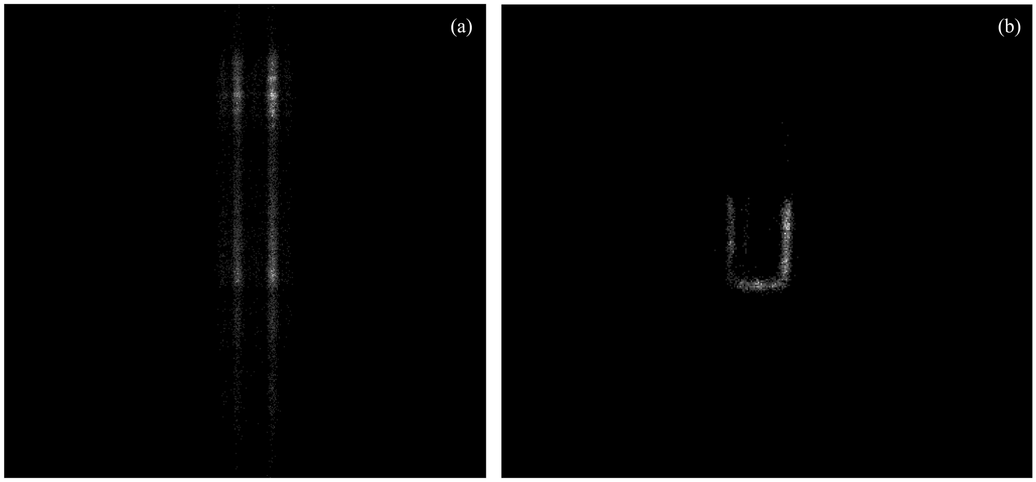

Fig. 11. (a) 2-slot imaging; (b) Capital "U" imaging.

4 Summary

The X-ray imaging device with delay-line readout is very efficient due to its ability to greatly decrease the cost of electronics and keep good spatial resolution. The spatial resolution of the delay-line readout method is greatly affected by the width and pitch of readout strips. Generally, smaller pitch or width can enhance the spatial resolution, but the distributing parameters will get worse. When a delay-line has a larger per-cell delay, the spatial resolution can be improved at the cost of counting ability [11].

Taking into account these factors, our device can achieve about 150 μm spatial resolution with two dimensional readout strips of 150 μm width on the top and 250 μm width on the bottom and has a good response in high rate environments up to 10^5 Hz/mm^2.

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