Nuclear Instruments and Methods in Physics Research A 674 (2012) 1–7

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Refinement of position resolution in two-dimensional X-ray detector based on μ-PIC gaseous detector

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ARTICLE INFO

Article history:
Received 27 March 2011
Received in revised form
11 January 2012
Accepted 19 January 2012
Available online 27 January 2012

Keywords:
Gaseous detector
Micro-pattern detector
X-ray detector

ABSTRACT

We have successfully refined the position resolution of a two-dimensional X-ray photon-counting detector based on the micro-pixel gas chamber (μ-PIC) by measuring the charge distribution of an X-ray interaction without the use of analog-to-digital converters (ADCs). By updating the logic of the Field Programmable Gate Arrays (FPGAs) included in the data acquisition system, we were able to acquire the pulse widths, or time-above-threshold of the μ-PIC signals, by measuring both the leading and trailing edges of the digital signals. By using the measured widths to estimate the peak of the charge distribution, the position resolution of our detector was improved to $\sigma = 93.3 \pm 2.8$ μm from a value of $\sigma = 229.5 \pm 6.8$ μm found using the FPGA logic of the previous system. This represents an improvement of nearly 60%.

1. Introduction

An X-ray area detector based on the micro-pixel gas chamber (μ-PIC) [1] has been developed and successfully applied to small-angle X-ray scattering (SAXS) at SPring-8, Japan [2]. The detector is a photon-counting-type gaseous detector offering advantages of time-resolved measurements and a wide dynamic range of counting rates. A detector with a wide dynamic range is preferable when conducting high-resolution measurements such as diffraction patterns and SAXS. Other kinds of detectors that are widely used in X-ray imaging include integration-type detectors such as imaging plates [3] and charge-coupled device (CCD)-based X-ray detectors [4]. Imaging plates provide high-resolution X-ray images and a wide dynamic range, but they require a long readout time after X-ray exposure and are not capable of fast time-resolved measurements. CCDs, on the other hand, offer time-resolved measurements, but dark current produces a background proportional to exposure time and limits the dynamic range. If a detector can count X-ray photons, it is free from the effect of dark current and has the potential to provide a wide dynamic range. The counting-type detector is also free from the long readout time and can generate time-stamped data, offering continuous, fast time-resolved measurements. Thus, it would have the advantages of both the imaging plates and CCDs, while minimizing the drawbacks. The μ-PIC is such a photon-counting detector and was previously shown to have a wide dynamic range of $>10^5$, as described in Ref. [2], and achieved continuous time-resolved measurements [5].

In our previous effort reported in Ref. [2], we did not reach the desired position resolution. The improvement of the position resolution is the focus of the present paper. In general, the position resolution can be reduced by creating a detector with a smaller pixel pitch or by introducing position interpolation using the charge deposited on each electrode as measured by analog-to-digital converters (ADCs). Reducing the pixel pitch is an inefficient way to refine the position resolution in gaseous detectors. Electron diffusion in a gas dominates the position resolution of a detector with a pitch of less than about 1 mm (i.e., a pixel size of the same order as the diffusion). Developing a detector with a fine pitch requires a long time and much effort but cannot improve the position resolution drastically by itself due to this diffusion effect. Alternatively, position interpolation has the potential to provide a fine position resolution with a moderate pixel pitch. For position interpolation, ADCs are frequently used to measure the charge deposition. However, for a μ-PIC with 512 readout channels, using ADCs would result in a system that is huge and complex. In place of ADCs, we used FPGAs (Field Programmable Gate Arrays) to build a compact system that is flexible and easy to handle. The use of FPGAs allows one to extend the system with low cost and incrementally improve the speed and performance through upgrades to the firmware.

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doi:10.1016/j.nima.2012.01.043

In Ref. [2], the position of an incident X-ray was calculated from the arithmetic mean of the individual hit positions. Under the previous FPGA logic, signals from the μ-PIC were discriminated and digitized, and the signals from the anodes and cathodes which coincided within 10 ns were stored and integrated to yield two-dimensional images. In the case that more than one anode or cathode strip recorded a hit during a 10 ns interval, only the arithmetic mean of the highest and lowest strips was returned. Since the positions were determined without position interpolation in the previous work, there was room for improvement in the position resolution. Instead of recording the charge deposition using ADCs, we used the FPGAs to measure the duration for which the μ-PIC signal exceeds the detection threshold, commonly known as the *time-above-threshold* but referred to throughout this paper as the pulse width (or simply as the width). As the ASDs already produce a digital signal with a width equal to this duration, it was a simple matter of upgrading the FPGA firmware to encode both the start and end of each digital signal and, thereby, measure the pulse width on each strip. This pulse width is strongly correlated to the charge deposition on the μ-PIC electrodes, and thus allows us to perform position interpolation for the X-ray interaction events.

2. Detector description

The μ-PIC, shown in Fig. 1, is a micro-pattern gaseous detector fabricated by printed circuit board technology. We used the same μ-PIC as in Ref. [2], with an active area of $100 \times 100\ \text{mm}^2$ and a pitch of 400 μm (manufactured by Dai Nippon Printing Co., Ltd.). The strip structure permits a 256×2 (=512) channel readout for 256×256 (=65,536) pixels. Each strip is instrumented with an amplifier and a discriminator arranged within Amplifier-Shaper-Discriminator (ASD) chips [6]. The ASDs convert charges from the μ-PIC to digital signals, providing a fast readout system.

The detector is contained within a sealed aluminum vessel with a 0.1 mm-thick polyimide entrance window and filled with a Xe–C_2H_6 (70:30) gas mixture at a pressure of 1 atm. The use of the polyimide window reduces absorption of 8-keV X-rays at the window to 10%. A Gas Electron Multiplier (GEM) [7] manufactured by Scienergy Co., Ltd., Japan, is positioned 3.5 mm from the μ-PIC and also 3.5 mm from the entrance window. The μ-PIC was operated at a gain of 2×10^3 with the GEM at a gain of 3 for a total gain of about 6×10^3. The electric field applied across the induction region was 3 kV/cm, and that across the drift region was 0.7 kV/cm, as shown in Fig. 1.

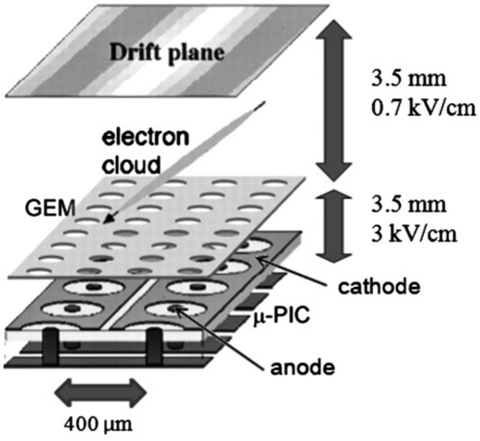

Fig. 1. The schematic of the X-ray area detector based on the μ-PIC. Above the μ-PIC, a GEM is installed and operated at a low gas gain.

2.1. The data acquisition system

An electron liberated from the gas by an X-ray photon absorption, referred to as the primary electron, travels ~ 1 mm before stopping, forming charged clouds of ions and electrons in the gas through ionization. The electron clouds drift along an electric field applied across the gas volume until they reach the μ-PIC. (The ions, being positively charged, drift in the opposite direction toward the drift plane.) As the electron clouds drift through the gas, collisions between the electrons and atoms of the gas result in an overall increase in the size of the cloud that is proportional to the drift distance (this process is known as diffusion). Considering the transverse diffusion coefficient of the Xe:C_2H_6 gas mixture provided by Magboltz [8] ($226\ \mu\text{m}/\sqrt{\text{cm}}$ in the drift region and $310\ \mu\text{m}/\sqrt{\text{cm}}$ in the induction region), the diffusion length for a cloud generated in the middle of the drift region is 206 μm, which is significant compared to our position resolution. Additionally, the longitudinal size of an electron cloud, which depends on the track length of the primary electron and the longitudinal diffusion, leads to a variation in the time when different parts of the electron cloud reach the μ-PIC. This time variation determines the rise time of the analog signals, and the variation in the amount of charge throughout the electron clouds causes time-walk in the ASDs. The leading edges of the digital signals generated by one X-ray were observed to be distributed within 50 ns on average. Thus, an X-ray interaction can be detected as a small cluster of signals covering several strips and distributed over several tens of nanoseconds.

A block diagram of the data acquisition (DAQ) system can be found in Ref. [2]. The electron clouds described above are amplified by the μ-PIC and collected on several anode and cathode strips. Next, the charges generated by the μ-PIC are amplified, shaped, and discriminated by the comparators contained within the ASDs to produce digital signals. These digital signals are then sent to an FPGA-based position encoding module [9], whose function, as well as the handling of the subsequent encoded data is discussed in the following sections.

2.2. Position encoding and calculation

Fig. 2 shows a schematic representation of the position encoding module, and a description of the hit encoding procedure follows. The FPGAs sample the digital signals at their leading and trailing edges, synchronize the signals with the internal clock of the FPGAs, and set an edge flag to 0 for edges with positive slope and 1 for edges with negative slope. The resultant data, including the position (10 bits), the time (20 bits), the edge flag (1 bit), and 1 bit to distinguish anode and cathode hits, are sent to a controller FPGA and stored temporally in a FIFO. The data words are then output via two 50-MHz 32-bit transfer lines to a memory board that can hold 32 MB (4 bytes $\times\ 8.4 \times 10^6$ data words), where they are stored until they can be read by a computer. The calculation of the positions of the X-rays are then performed off-line. The time resolution is determined by the internal clock of the FPGAs (10 ns per clock pulse).

In the previous system, only the leading edges were sampled, and then, only those anode and cathode hits whose leading edges coincided within one 10-ns clock pulse were recorded for later analysis. The new functionality added in this work is the ability to also record the trailing edges, allowing one to calculate the widths of the digital signals. The coincidence condition, which was found to reject many real hits due to the time-walk of the ASDs, was also lifted, allowing for a more complete reconstruction of each X-ray event.

In the updated FPGA logic, the width gives the duration for which a μ-PIC signal exceeds the detection threshold, as illustrated in