HIGH SPEED SIGNAL PROCESSING FOR PHOTON COUNTING X-RAY DETECTION

B. Shinomiya, A. Koike, H. Morii, T. Okunoyama, Y. Neo, H. Mimura, Toru Aoki

Abstract:

Recently practical X-ray measurement systems are demanded energy distinction function. Photon-counting CdTe semiconductor detectors have a high energy resolution in a low count rate condition at room temperature. However, the energy resolution is decreased by pile-up phenomenon in a high count rate condition. In conventional signal processing, processing time estimated X-ray photon energy from the pulse waveform is about tens of microseconds. This time is depended on the pulse decay time. This paper purposes to maintain the high energy resolution by changing the signal-processing algorithm, which derived the pulse rise height of the output waveform from the CdTe detector in a high count rate condition. As a result, the pulse rise time required to estimate the pulse rise height was short about 100 ns at incident X-ray energy 60 keV. As the result of energy spectrum by using this data, the FWHM of about 11keV (at 60 keV) when the count rate of 500 kcps. This result shows the possibility that the photon counting sensor has application for the high count rate imaging without decrease of the high energy resolution.

Keywords: *X-ray, CdTe, photon counting.*

1. Introduction

X-ray radiography is a method which insight information of the object can be inspected non-destructively. Recently, there is a demand of obtaining material information such as atomic number and electron density in addition to insight shape information. The material discriminated X-ray computed tomography system which for obtaining was had been already reported by using conventional micro-focused X-ray tube and photon counting type CdTe X-ray imager with X-ray energy information [1]-[4]. A photon-counting method is used for obtaining the X-ray energy information and atomic number mapping images were estimated by photon energy information. A photon-counting imaging method make usually slow imaging method because the photon-counting have to treat the incident X-ray photons individually. Therefore, there is a request for using a photon-counting in a high incident rate for fabrication the high-speed X-ray imager and the real-time X-ray imager with energy information.

Figure 1 shows block diagram of conventional signal processing of photon counting method by multichannel analyzer (MCA). Waveform from preamplifier is shaped to integral waveform with decay curve by analog integrator inside MCA. Crest value of the integral waveform is converted analog information into digital information, and this digital crest value is treated as an incident X-ray photon energy.

The CdTe semiconductor detector used conventional signal processing has a high energy resolution in a low count rate condition at room temperature. However, the energy resolution is decreased by pile-up phenomenon in high count rate.

Therefore, in this paper, we tried proposing a new signal processing (pulse rise height signal processing) used without degradation of energy resolution even if pile-up is occurred.

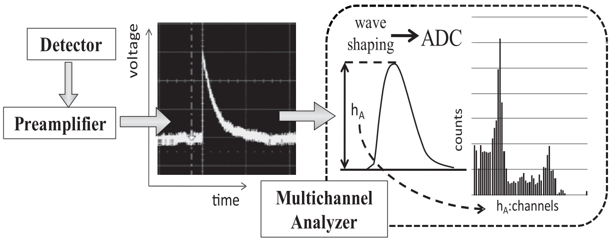

Fig. 1. Block diagram of conventional signal processing of the photon-counting.

2. Principle

2.1. Estimation method of X-ray phone energy

The pulse rise height which changed shape by preamplifier is proportional to the x-ray energy. We considered that we can obtain the each photon energy by using the pulse rise height even if pile-up is occurred, and this signal processing is adapted for more high count rate condition than for conventional signal processing. It is because that the pulse rise time is considerably faster than the pulse decay time. The time which obtained the X-ray energy is considerably faster than conventional signal processing used the area of pulse by using pulse rise height.

Experimental system was used the CdTe n-π-n diode detector (2x2x0.5 mm-thick) (electrode: n-In, p-Au) under 200 V bias at room temperature, the preamplifier (Clear Pulse) and Am-241 radioisotope as a checking source. The output of preamplifier was connected to digital storage oscilloscope (DSO: Lecroy WS452), and each data saved in oscilloscope was analyzed.

2.2. Analytical method for obtaining pulse rise height

In Fig. 2, solid line shows the data obtained from DSO, and dash line shows 50 ns moving average line of solid line. For obtaining the pulse rise height, the two points which before and after pulse rising are had to decide.

Therefore, we decide the two points which gradient value is about 0 in before and after pulse rising from the moving average line. The pulse rise height was obtained by assigning those different two points which gradient value is about 0, as shown allow line in Fig. 2.

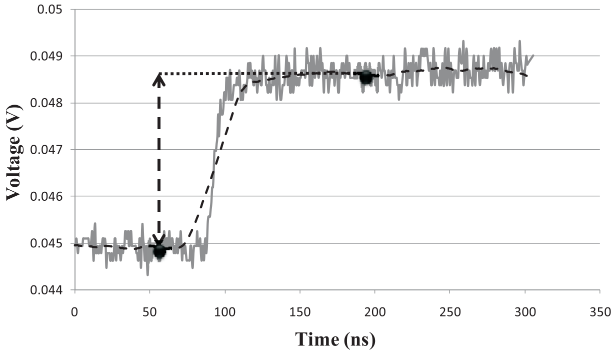

Fig. 2. Analytical method for obtaining pulse height. Solid line is the oscilloscope data obtained from the preamplifier. Dash line is 50ns moving average line of the continuous line.

3. Experiment and result

We carried out three kinds of experiments. First experiment shows comparison the pulse rise height signal processing and conventional signal processing used MCA in two condition of non pile-up and in pile-up. Second experiment is run in a high count rate condition of less 1 Mcps by using the pulse rise height signal processing. In third experiment, atomic number and electron density was obtained by using the pulse rise signal processing.

3.1. Experiment in two condition of non pile-up and in pile-up

We carried out experiments in a non pile-up and a pile-up by using the pulse rise height signal processing and conventional signal processing used MCA. Preamplifier was used Clear Pulse-5102B. (Rise time is about 500 ns, the pulse attenuation constant is 60 µs.) Fig. 3(a) was output waveform from DSO in a few kilo cps of non pile-up condition. Fig. 3(b) was output waveform from DSO in about 50 kcps of pile-up condition.

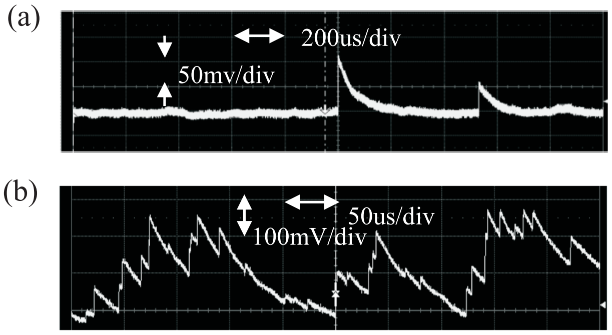

Fig. 3. Those two figures show digital signal waveform from oscilloscope when Am241 was used. Fig.(a) was output waveform from DSO in a few kilo cps of non pile-up condition, gamma source was Am of 3.7Mbq x 1, distance of detector and gamma source was 200 mm. Fig.(b) was output waveform from DSO in about 50k cps of pile-up condition, gamma source was Am of 3.7Mbq x 3, distance of detector and gamma source was a few millimeter.

In Fig. 4(a), (b), those two energy spectrums show that the conventional signal processing by MCA and the pulse rise height signal processing have same high energy resolution, and two energy spectrums (b), (d) show that non pile-up condition and pile-up condition have same high energy resolution of 4 keV by using the pulse rise height signal processing. On the other hand, energy resolution of 20 keV in Fig. 4(c) was 5 times as large as Fig. 4(a). The FWHM were estimated by energy proofed from channel.

This experiment showed high energy resolution was maintained up to about 50 kcps condition by using the pulse rise height signal processing. But count rate was only 50 kcps, our aimed count rate condition is over 1 Mcps. Therefore, next experiment condition was high count rate condition in over 50 kcps.

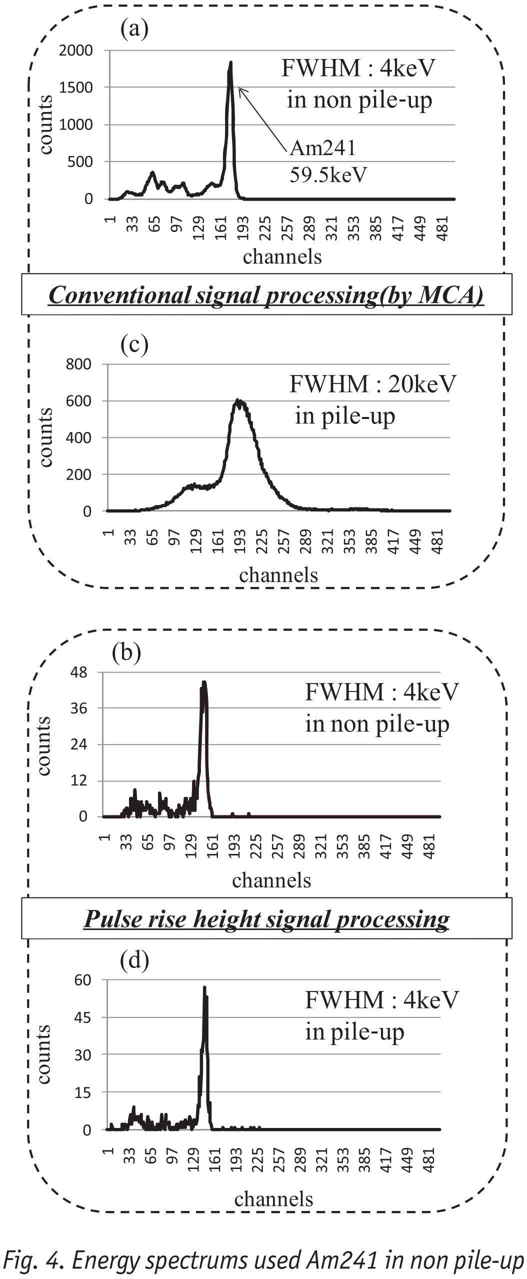

Fig. 4. Energy spectrums used Am241 in non pile-up and pile-up. (a)(c) two figures were used the conventional signal processing, and (b)(d) two figures were used the signal processing of the pulse height. (a)(b) two figures is in non pile up shown (a) Fig. 3, and (c)(d) two figures is in pile-up shown (b) Fig. 3.

3.2. Experiment in high count rate condition

We carried out experiment by using the pulse rise height signal processing in a high count rate condition. In order to measure energy spectrum in a high count rate condition, white X-ray tube source was used together with Am241 which as checking source. This experimental block diagram is shown in Fig.5, the fast preamplifier was Clear Pulse-5015S. (Rise time is about 100 ns, the pulse attenuation constant is 60 µs), and measurement time of each energy spectrum was 30 ms.The voltage of white X-ray tube was 40 kV, and Am241 has main peak energy of 59.5 keV.

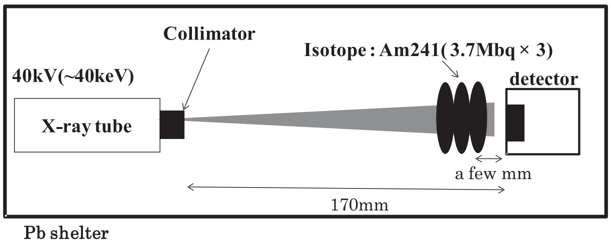

Fig. 5. Schematic of measurement system. X-ray tube voltage was 40kV. X-ray tube current was 0, 20, 50, 80 µA. The distance of X-ray tube and detector was 170 mm, Am241 and detector was a few millimeter.

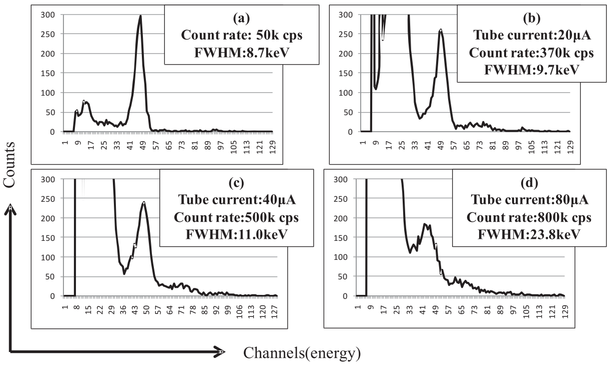

Fig. 6. Energy spectrums used white X-ray and Am241 in high count rate condition by a using fast preamplifier (CP-5015S). Figure (a) is used only Am241. Figure (b), (c) and (d) was used Am241 and white X-ray. X-ray tube vol-tage is 40 kV. Preamplifier is CP5015S (Rise time is about 100 ns by using Am241. The pulse attenuation constant is 60 µs).

In Fig. 6, the count rate was become higher with increase of the X-ray tube current. Those energy spectrums shown in Fig. 6 show the gradation of energy resolution with a high count rate and unoriginal counts at high energy region with high count rate. We considered that the origin of degradation of energy resolution with a high count rate and the origin of increase of unoriginal counts at high energy region with high count rate are increase of the overlap of previous and next pulse at the leading edge with high count rate. However, when count rate was 500 kcps in Fig. 6 (c), energy resolution was 11.0keV. This energy resolution was only 2.3keV lager than the reference energy resolution 8.7keV which used only Am241 as shown in Fig. 6(a). We couldn't find so large degradation of energy resolution up to 500 kcps condition. From a result of this experiment, in 300 kcps which is ten times from experiment condition used the conventional signal processing, degradation of energy resolution degrease from reference energy resolution is less than 1.0 keV, and energy resolution is not over 9.7 keV. In next experiment, we tried to obtain effective atomic number in 300 kcps condition for checking the accuracy of atomic number.

3.3. Obtaining effective atomic number and electron density

Energy spectrum was measured by using the pulse rise height signal processing in 300 kcps condition, and effective atomic number and electron density was calculated by using the calculation technique of dual energy X-ray CT (DXCT). The DXCT's theory is as follows [5], [6].

3.3.1. Measurement effective atomic number and electron density

In this section, effective atomic number and electron density of Al plate were obtained by used expressions calculated effective atomic number and electron density of DXCT from µ of experimental value. Fig. 7 shows schematic of measurement system. Detector and preamplifier (fast amp: CP5015S) were same as for previous experiment 3.3, and incident X-ray energy was obtained by using the pulse rise height signal processing. X-ray tube voltage was 150 kV. X-ray tube current was 10 µA. Sample was 20 mm-thick Al plate.

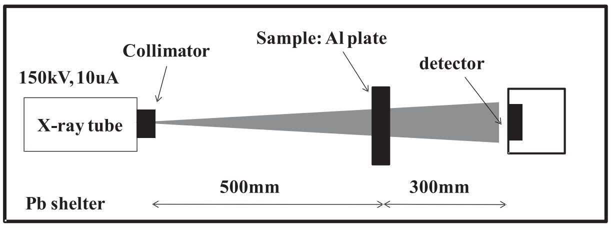

Fig. 7. Schematic of measurement system. X-ray tube voltage was 150 kV. X-ray tube current was 10 µA. Sample was 20 mm-thick Al plate. The distance of X-ray tube and sample was 500 mm, sample and detector was 300 mm.

Table1 shows that results of experiment for obtaining effective atomic number and electron density, and effective atomic number was 13.1 and electron density was 1.21×10^{24} cm^{-3}, count rate was 300 kcps, energy resolution estimated from previous experiment 3.3 in this count rate was about 10 keV, total photon count (10~150 keV) was 60 k counts, Minimum measurable energy was about 10 keV, and two energy range used in the calculation technique of DXCT were 35-50 keV and 85-90 keV.

Table.1 result of experiment for obtaining effective atomic number and electron density of Al plate.

Effective atomic number	13.1
Electron density	1.21×10^{24} cm^{-3}
Measurement time	0.2 s
Count rate	300 kcps
Total count	60k counts
Energy resolution	About 10 keV
Utilizable energy range	10~150 keV
Energy range used in DXCT	35-40 keV, 85-90 keV

3.3.2. Estimation of a relationship between effective atomic number and total photon count

Fig. 8 shows effective atomic number and electron density when total photon count was decreased from 60k counts. As total count lower than about 36k counts, error of effective atomic number was bigger than 13: atomic number of Al. Energy spectrums in total count rate condition of 60k counts and 15k counts were shown in Fig. 9. In Fig. 9, shapes of spectrums transmitted Al plat conformed in each total count condition. On the other hand, Fig. 9 shows different shape of spectrums transmitted no sample in each total count condition between 25 keV and 55 keV. The differences of shape cause increase in error of atomic number to theoretical atomic number. We consider, by choosing appropriate two energy range, there is a possibility that high calculation accuracy obtained effective atomic number and electron density is obtained in a low total photon count condition.

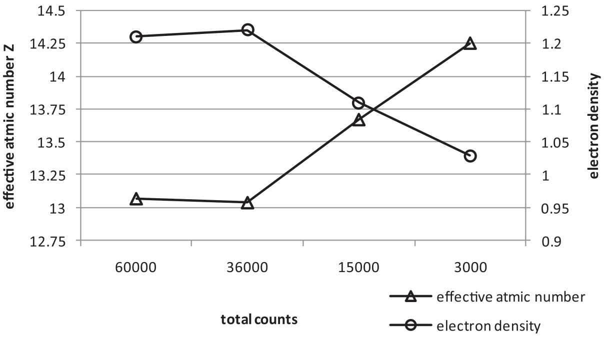

Fig. 8. Change of effective atomic number and electron density when total photon count was decreased from 60k counts.

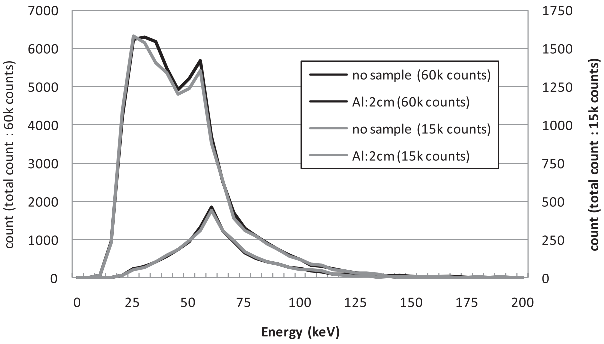

Fig.9. Energy spectrums in total count rate condition of 60k counts and 15k counts.

4. Conclusion

We have proposed the decrease of degradation of energy resolution with high count rate by using the signal processing of using pulse rise height in pile-up condition. We could obtain about the same energy resolution (4 keV) as conventional signal processing in non pile-up and we could maintain this energy resolution even if pile-up is occurred. Moreover, we showed that energy resolution 11.0 keV in about 500 kcps, and we couldn't find so large degradation of energy resolution with the high count rate. So, there is a possibility used the photon counting in the high count rate condition without decrease of the high energy resolution. Effective atomic number of Al plate sample was shown 13.1 in 300 kcps condition and a possibility that obtaining higher-accuracy effective atomic number with fewer total photon count. Those results are indicated the possibility that the photon counting sensor has application for high speed imaging.

AUTHORS

B. Shinomiya*, A. Koike, H. Morii, T. Okunoyama, Y. Neo, H. Mimura, Toru Aoki - Research Institute of Electronics, Shizuoka University, Hamamatsu, Japan.
E-mail: shinomiya@nvrc.rie.shizuoka.ac.jp.
* Corresponding author

References

[1] Nilaura M., Nakamura A., Aoki T., Hatanaka Y., *Phys. Stat. Sol. B*, no. 229, 2002, pp. 83-87.

[2] Aoki T., Ishida Y., Sakashita D., Gnatyuk V.A., Nakamura A., Tomita Y., Hatanaka Y., Temmyo J., "Development of energy discriminated CdTe imaging detector for hard X-ray". In: *Proc. SPIE 5540*, 2004, pp. 196-205.

[3] Aoki T., *et al.*, *IDW/AD'05*, 2005, p. 4283.

[4] Zou W., Nakashima T., Onishi Y., Koike A., Shinomiya B., Morii H., Neo Y., Mimura H., Aoki T., "Atomic Number and Electron Density Measurement Using Conventional X-ray Tube and a CdTe Detector". *Japanese Journal of Applied Physics*, vol. 47, no. 9, 2008, pp. 7317-7323.

[5] Ohno Y., Torikoshi M., Tsunoo T., Hyodo K., "Dual-energy X-ray CT with CdTe array and its extension". *Nuclear Instruments and Methods in Physics Research*. *Section A*, no. 548, 2005, pp. 72-77.

[6] Torikoshi M., Tsunoo T., Endo M., Noda K., Kumada M., Yamada S., Soga F., Hyodo K., "Design of synchrotron light source and its beamline dedicated to dual-energy X-ray computed tomography", *Journal of Biomedical Optics*, vol. 6(3), 2001, pp. 371-377.