A FPGA-based Pulse Pile-up Rejection Technique for the Spectrum Measurement in PGNAA

Chen Lian, Liang Futian, Liu Yuzhe, Li Feng, and Jin Ge

***Abstract*–In this paper, a FPGA-based pulse pile-up rejection method for the high count rate gamma spectrometer of PGNAA is reported. By using fast peak seeking and feedback control, the pulse width can be narrowed then the pile-up events will be reduced. Test results shown that the energy resolution of the spectrometer is closed to the commercial products. For a count rate of 400 kHz, the number of pile-up events is reduced by 15.84%. This method is easy to implement in FPGAs for real-time data processing.**

I. Introduction

PROMPT gamma neutron activation analysis (PGNAA) is a non-destructive nuclear analytical technique for the determination of elements. It is widely used for online and in situ measurement. The method is based on the detection of prompt gamma-rays which are emitted from thermal neutron capture or neutron in-elastic scattering reactions. The prompt gamma energy from such reactions is characteristic to the elements present in the sample. By measuring the prompt gamma spectrum, elements of the sample material can be distinguished, and the element composition can be obtained through the gamma line ratios[1], [2].

As an on-line inspection method, the PGNAA technique need to acquire an accurate spectral information in a relatively short measurement time. Consequently, the high count rate gamma-ray spectrometer plays an important role of the PGNAA technology.

II. Pulse Pile-up and Baseline Restorer

The prompt gamma in PGNAA follows the Poisson distribution. For a constant given counting rate R, the probability of observing n events in a time interval ΔT can be given by [3]:

$$P(n,\Delta T)=\frac{(R\Delta T)^n}{n!}e^{-R\Delta T} \tag{1}$$

If two or more events are recorded within ΔT, the pile-up ruins the energy determination of the later events which should be rejected from the results. The counting loss P_{Loss} within ΔT is:

$$P_{Loss}\approx 1-P(0,\Delta T)=1-e^{-\bar{n}\Delta T} \tag{2}$$

In high count rate nuclear instrumentation applications, the detectors and the front-end electronics, especially the pulse post-pile-up would cause a signal baseline drift which will degrade the performance of energy resolution[4].

In order to reduce the influences of pile-up and baseline fluctuation, the pulse duration of the shaped signal should be as narrow as possible. However, to improving the signal-to-noise ratio (SNR), the signal is usually shaped to a Gauss waveform which has a long tailing edge. To satisfy these two conflicting demands, a new method of pulse pile-up rejection based on FPGA is shown in this paper.

III. System Design

A. Shaping Method

In nuclear signal detection, the CR-$(RC)^m$ shaping circuit is widely used to get a quasi-Gaussian waveform. The scheme of the shaping circuit is shown in Fig. 1.

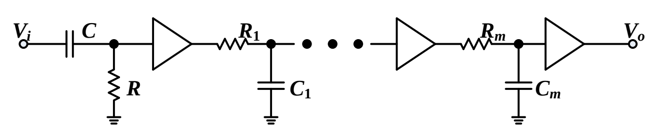

Fig.1 Schematic diagram of the CR-$(RC)^m$ shaping circuit

The pulse response of the circuit $h(t)$ could be deduced by invert Laplace transform $L^{-1}[H(s)]$ with $RC=R_1C_1=\cdots=R_mC_m=\tau$:

$$h(t)=\frac{1}{m!}\cdot(\frac{t}{\tau})^m e^{-t/\tau}\cdot u(t) \tag{3}$$

Then the shapes pulses $s(t)$ can be modeled as follows:

$$s(t)=U\cdot\lambda\tau\cdot(e^{-\lambda t}-e^{-t/\tau}) \tag{4}$$

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Chen Lian, Liu Yuzhe, Li Feng, and Jin Ge are with the State Key Laboratory of Particle Detection and Electronics, University of Science and technology of China, Hefei, China (e-mail: chenlian@ustc.edu.cn; yuzheliu@mail.ustc.edu.cn; phonelee@ustc.edu.cn; goldjin@ustc.edu.cn).

Liang Futian is with the Hefei National Laboratory for Physical Sciences at the Microscale, University of Science and technology of China, Hefei, China (e-mail: ftliang@ustc.edu.cn)

where λ is the fluorescence decay time constant of the detector[5], [6].

The shaped pulse width can be reduced by decreasing the shaping time. However, the apparent gain is offset by a loss in the energy resolution which leads to a decrease in the pulse amplitude. If the tailing edge of the shaped pulse can quickly return to the baseline after the peak collecting, then the pulse width will be reduced and the energy information is preserved.

B. Pile-up Rejection Method

A pile-up rejection method, which a feedback signal is used to discharge the capacitor in the shaping circuit, is developed. The scheme of the technique is illustrated in Fig. 2.

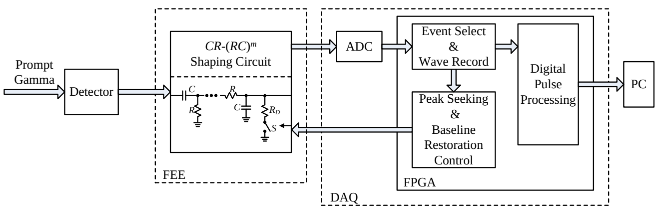

Fig.2 Schematic diagram of the pile-up rejection method

The signal generated by the detector passes the $CR\text{-}(RC)^m$ shaping circuit and becomes a quasi-Gaussian pulse. The pulse is digitalized by the analog-to-digital converter (ADC). The digital signal is discriminated and recorded in field-programmable gate array (FPGA). Once the pules peak is found, a feedback signal is send back to the shaping circuit and control an analog switch to discharge. Then the tailing edge of the pulse is cut off quickly, the pulse width will be narrowed and the pile-up events will be reduced. At the same time, the signal baseline is restored, the influence of baseline drift will be also suppressed.

C. Application Limits

The signal processing time T contains the ADC conversion time t_{AD}, the peak seeking time $t_{PS,}$ the discharge time t_D, the baseline restoration time t_R, the signal transmission time t_T, and so on. Therefore, the time T can be describe as:

$$T \approx t_{AD} + t_{FP} + t_D + t_R + t_T \tag{5}$$

The time t_T and t_{AD} are determined by the transmission line and the ADC. The time t_D and t_R are determined by the analog switch. The length of the additional times will limit the highest count rate of the system.

IV. EXPERIMENTAL RESULTS

A high count rate gamma spectrometer is designed for PGNAA. The shaping circuit using $CR\text{-}(RC)^4$ method. The shaped signal is converted by a 14-bit ADC (Texas Instruments, AD9643) with a 250 MSPS sampling rate. The analog switch TS5A1066 (Texas Instruments) is chosen for the feedback discharge control. According to Equation 5, the signal processing time of the spectrometer is not less than 200ns.

An energy spectrum of ^{60}Co is measured by the spectrometer. The scheme of the experiment is described in Fig. 3. The BGO detector and Photonis XP3540 photomultiplier (PMT) are packed together in an aluminum alloy barrel. A ^{60}Co radiation source places in front of the detector. The high-voltage power supply (ORTEC, 556) provides operating voltage for the PMT. The ORTEC lanBase commercial product is constructed for comparison.

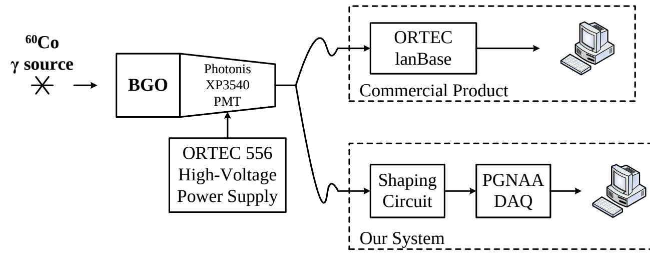

Fig. 3 The schematic diagram of γ energy spectrum measurement

The *RC* constant of the shaping circuit is 50 ns. The resulting pulse duration is about 500 ns. A typical 2-pile-up events from the shaping circuit are shown in Fig. 4. The pile-up causes error in the later pulse amplitude measurement, thus the second signal should be rejected. However, the two signal are complete separated with baseline restoration.

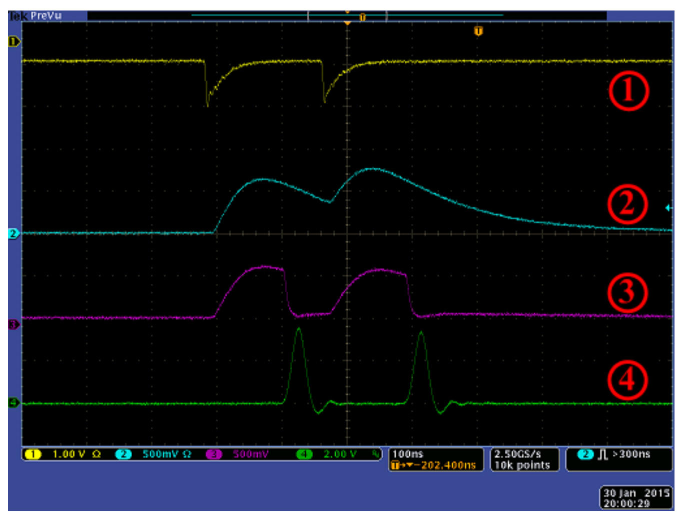

Fig. 4. Test result of the shaping circuit, (1) the two signal generated by PMT in a short time interval; (2) the pile-up cause errors in the second signal amplitude measurement; (3) the two signal are complete separated by using quick baseline restoration; (4) the feedback control signal.

The energy spectrum of both analyzer are shown in Fig.5. For a count rate of 8 kHz, the energy resolutions of 1.33 MeV gamma-rays of the ORTEC lanBase and our system, which covers the BGO detector and the XP3540 PMT, are 8.9% and 8.78%.

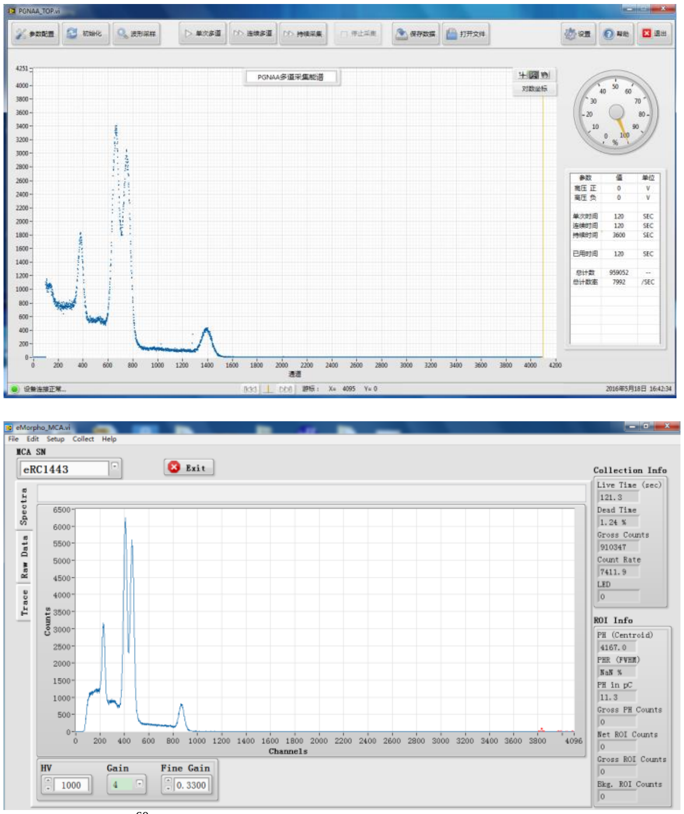

Fig. 5. The ^{60}Co gamma spectrum acquired by PGNAA DAQ (top) and the ORTEC lanBase (bottom).

The results of count loss for different count rates are shown in Table I. At low count rate, there is almost no difference between with and without feedback control. For a count rate of 400 kHz, the number of pile-up events is reduced by 15.84%, compared to the spectrum without the pile-up rejection method.

TABLE I. RESULTS OF COUNT LOSS

Count rates	Count Loss		
	ORTEC lanBase	Our system without feedback	Our system with feedback
8k	1.24%	1.02%	1.01%
20k	7.87%	5.98%	5.00%
50k	13.75%	8.87%	6.46%
100k	25.11%	12.51%	9.87%
400k	68.21%	41.96%	26.12%

V. CONCLUSIONS

In this paper, we presented a pulse pile-up rejection method based on FPGA for the gamma spectrometer of PGNAA. The test results show that the pile-up rejection method can effectively reduce the impact of pulse pile-up. The energy resolution @ 1.33 MeV gamma-rays of the system is 8.78% which close to the commercial products. For a count rate of 400kHz, the number of pile-up events is reduced by 15.84%, compared to the spectrum without pile-up rejection method.

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