An Adaptive γ-Ray Spectrometer with a High Event Processing Rate

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Abstract—A fast γ-ray spectrometer adaptable to the scintillator type is described. This spectrometer is capable of processing a γ-ray energy spectrum (with a resolution of <4% in the energy range from 20 keV to 10 MeV) in a sequence of time intervals in the real-time mode at a counting rate of up to \(10^6\) cps. Digitization of the detector signals by a 14-bit ADC with a sampling rate of 64 MHz and real-time data stream processing are used to separate overlapping events and correctly generate energy spectra.

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INTRODUCTION

γ-Ray spectroscopy is one of the best techniques providing comprehensive information on the object of investigation. Apart from plasma physics research and controlled fusion, its spheres of application are nuclear physics, geophysics, medicine, and complexes of equipment for identification of the chemical composition of various objects. In all these applications, particularly in investigations of processes in high-temperature plasmas, special emphasis is placed on information about the variations of photon energy spectra over time. To obtain this information, one must use equipment capable of forming such spectra over the shortest possible time so that their statistics is sufficient for analysis. In turn, this is possible only when the counting rate is high and high-efficiency procedures are used in the data acquisition process to separate overlapping events.

Integrating analyzers are traditionally used in γ-ray spectroscopy owing to the high integral and differential linearity. In analyzers of this type, the analog signal from a detector composed of a scintillator and a photomultiplier tube (PMT) is integrated on a time interval that is longer than the characteristic luminescence decay time of the scintillator. The obtained results are thereafter digitized by the ADC and transmitted to the digital processing module, which forms the energy spectrum in its autoincrement storage unit (ASU) \[1\]. The high energy resolution and the wide dynamic range for signals with a long pulse fall time and a low repetition rate are the advantages of these spectrometers. Their drawbacks are determined by the following characteristics of the integration module:

— the long dead time associated with the release of the charge accumulated from the previous event on the integrating capacitor;
— the pulse height uncertainty due to the zero offset voltage of the integrator;
— the low temperature stability attributable to the integrating capacitor;
— deterioration of the energy resolution in the course of time, caused by the ageing of the integrator components; and
— the low energy resolution for broadband signals, which depends on the frequency error of the operational circuits.

Measures taken to eliminate these drawbacks fail to provide an overall result. For example, using auxiliary analog filters transforming the detector signal waveform, one can reduce the signal duration and, thereby, increase the throughput of the data acquisition section. These filters allow the noise level to be lowered and the zero line position to be stabilized. However, a decrease in the characteristic signal duration entails more stringent requirements for the frequency characteristics of the integrator, which is the key component of the spectrometer. The other demerit of this solution is the fact that the use of shaping analog filters makes it impossible to change the scintillator type without changing the parameters of the data acquisition section.

All these drawbacks can be eliminated by changing over to the circuit of the measuring section, in which the detector signal is digitized by the ADC with an increased digit capacity and a high sampling rate. The counting rate of such a spectrometer can be increased by involving high-efficiency procedures for digital processing of ADC counts aimed at separating overlapped events. The simplest and most vivid method is based on transforming the original detector signal presented by a sequence of ADC counts into a short Gaussian pulse with an amplitude proportional to the γ-ray energy \[2, 3\]. The procedure for producing such
a pulse is reduced to constructing a digital filter with the required pulse characteristic.

A METHOD FOR SEPARATION OF OVERLAPPING EVENTS

The direct and inverse Fourier transforms have been used to construct the shaping filter. Using the convolution procedure for filter’s pulse characteristic \( h(t) \) with detector signal \( u(t) \)

\[
g(t) = h(t) \ast u(t)
\]

the shaping filter converts detector signal \( u(t) \) into short Gaussian-shaped signal \( g(t) \), which is convenient for pulse height measurements. In the spectral representation, the convolution procedure is replaced by the product of spectral images

\[
G(f) = H(f)U(f),
\]

therefore, the spectral characteristic of the shaping filter is

\[
H(f) = G(f)/U(f).
\]

The pulse characteristic of the filter is determined using the inverse Fourier transform \( H(f) \leftrightarrow h(t) \).

The possibility of realizing \( h(t) \) is determined by the stability of the solution to Eq. (1) and depends on the frequency characteristics of signals \( u(t) \) and \( g(t) \). Among the necessary conditions for correct realization of \( h(t) \) are (i) the absence of poles in function \( U(f) \) to avoid division into zero and (ii) a faster decay of \( G(f) \) relative to \( U(f) \).

As \( g(t) \), one should select the Gaussian function with the full width at half-maximum (FWHM) such that its spectrum in the significant part is comparable to the spectrum of signal \( U(f) \). It is apparent that, the smaller the FWHM of \( g(t) \), the higher the efficiency of the signal compression procedure and, therefore, the procedure of overlapping-event separation. Nevertheless, upon excessive compression of \( g(t) \), function \( h(t) \) will significantly raise the RF components of detector signal \( u(t) \), which will cause the signal-to-noise ratio to decrease. In view of the causality factor, the output signal of the shaping filter is expected to appear beyond the leading edge of signal \( u(t) \), and its extremum lies beyond the extremum of the detector signal. Taking into account that the shaping filter is linear and that it embodies the principle of superposition of the input signals, this filter responds to the sum of the previous detector signals at any current instant of time. Therefore, if the pulse characteristic of the filter is calculated so that its response to a unit detector signal precisely reaches the zero line in a short period time, this property will be retained whether single or overlapping signals arrive at its input.

NUMERICAL SIMULATION OF THE PROCEDURE OF OVERLAPPING EVENT SEPARATION

To test the procedure for separating the overlapping events by means of the shaping filter, it was numerically simulated in the MathCAD environment using a model in which the detector signal is described by two exponentials

\[
u(t) = A \left( e^{-\frac{t}{\tau_1}} - e^{-\frac{t}{\tau_2}} \right),
\]

where \( A \) is the signal amplitude, and \( \tau_1 \) and \( \tau_2 \) are the pulse fall and rise times, respectively (Fig. 1a).

The desired filter response is presented by the Gaussian pulse with a duration shorter by the order of magnitude than the fall time of the detector signal and with the amplitude proportional to the amplitude of this signal:

\[
g(t) = Ae^{-\frac{b^2}{2\sigma^2}},
\]

where \( A \) is the signal amplitude, \( b \) is the delay time of the filter response with respect to the input signal, and \( \sigma \) is the duration of the resultant signal.

The significant part of the filter’s spectral characteristic was extracted by multiplying it into the weight function

\[
P(f) = (1 + f^2/k)^{-1},
\]

where \( k \) is the coefficient determining the passband of the weight function, and \( c \) is the coefficient responsible for the rate of decline of the weight function, which is equal to unity with a high accuracy within the margins of the significant part of ratio \( G(f)/U(f) \) and falls to zero beyond these margins.

This function is used to suppress RF noise of the input signal. Resultant spectral distribution \( H(f) \) has the shape shown in Fig. 1b. The behavior of the pulse characteristic of the shaping filter \( h(t) \), calculated using the inverse Fourier transform, is presented in Fig. 1c.

It is apparent that the resultant pulse characteristic of the filter is finite, decays rather fast, and can be limited by the time required for measurement of \( t_b \) counts. Such a filter can be designed using an analog circuit, but tuning its characteristics to the detector signal parameters will be rather laborious. In this respect, the digital filter has better capabilities [its error was estimated during numerical simulation of the convolution of its pulse characteristic \( h(t) \) with detector signal \( u(t) \)].

Since the amplitude of the output signal from the filter is proportional to the \( \gamma \)-ray energy, the filter conversion error in the vicinity of the detector signal maximum is very important for spectrometric applications. Errors resulting from the spectrum truncation and the limitation of the array of points describing the pulse characteristic of the filter using appropriate coefficients were compensated for by correcting the values of the final terms in this array, whereas the precise