Digital trigger system for the RED-100 detector based on the unit in VME standard

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Abstract. The system for forming a trigger for the RED-100 liquid xenon detector has been developed. The trigger can be generated for all types of events required to calibrate the detector and data acquisition, including events with one ionization electron. The system has an event detection mechanism where each event is assigned with the timestamp and event type. The trigger system is required in the systems searching for rare events to keep only the necessary information from the ADC array. The characteristics and implementation of the trigger system that provides high efficiency operation even at low-energy events have been described.

1. Introduction

International scientific collaboration COHERENT [1] with the participation of Laboratory for experimental nuclear physics MEPhI created RED-100 detector which is designed to search and study the effect of coherent elastic neutrino-nucleus scattering (CENNS) [2, 3]. Spallation Neutron Source (SNS), Oak Ridge National Laboratory (USA) is considered as a source of neutrinos for measurement. Because of the smallness of the neutrino energy from source expected recoil energy is very low (<10 keV).

The RED-100 experimental setup is a two-phase liquid xenon time projection chamber [3]. The principle of operation of such detectors is illustrated in figure 1. Particles interacting with dense noble liquefied gas medium produces excitation and ionization. The excitation creates prompt scintillation (S1 signal). Under the influence of the applied electric field ionization electrons drift along applied electric field towards the surface and then enter into the vapor phase where produce proportional scintillation or electroluminescence (S2 signal). The time difference between S1 and S2 signals defines Z position of the event, while the X-Y position is determined from the pattern of S2 light in the photodetecting system. The 3D event reconstruction allows to define a fiducial volume eliminating potentially background events originated in the vicinity of the detector walls. Measurement of the ratio of S2 to S1 signal amplitudes gives an ability to discriminate between electron recoils and nuclear recoils providing an efficient background rejection.
Detectors of this type are widely used in measurements of low-energy recoil to search for dark matter [5]. A distinctive feature of emission detectors is the significant (to a few hundred photons per electron) ionization yield of electroluminescence. This allows you to achieve very high sensitivity, up to the registration of single electron ionization (SE) [4]. With such low-energy electroluminescence signal is divided into its component signals of single photoelectrons (SPE), distributed along the entire length of the electroluminescent signal, which in this case is significant 2 microseconds.

In the RED-100 detector light signals are registered by two arrays of 19 PMTs each located above and below the active volume (see figure 1). The energy range of ionization from one electron is up to 100 keV, which corresponds to the total number of photons detectable from $10^2$ to $5 \times 10^5$. This puts high requirements on the trigger generation scheme (both the lower threshold and the dynamic range).

2. Statement of the problem

Usually simple discrimination of signals in the overall channel after smoothing filter provides the trigger on scintillation and luminescence. In the experiment on SNS expected useful signal is less than 10 SE, which requires a low threshold of the trigger to be lowered to the level of several SE. Amplitude resolution of single-photon pulses PMT is quite large (FWHM $\approx$ 100%), which in the case of analog signals summation lead to high errors in estimating the amount of SPE. The effect of spontaneous emission SE [4,6] creates a background signal greater than useful signal by 2-3 orders [2]. The use of discriminators for each channel, and then the analog summation significantly improves the amplitude resolution, but can be still insufficient. An additional problem is that the scintillation signals can provide the same amount of SPE as SE, thus have much higher energy and have to be excluded by trigger. To fulfill all requirements for a trigger it was decided to use discriminators in each channel and the digital circuit (Field-Programmable Gate Array - FPGA), receiving signals and precisely counting the incoming SPE.

To implement the required functionality it was decided to use a CAEN V1495 digital module with custom firmware and 3 CAEN V895 discriminator modules. The use of FPGA unit in V1495 simplifies modification and enhances capabilities of the trigger system. Firmware Development program was carried out with the use of computer-aided design (CAD) Quartus 9.1.
3. Implementation of the trigger system

The signals from each PMT come to individual discriminators configured to activation on the SPE, and then go straight into the digital module V1495. The internal structure of the digital module can be divided into four parts: counting units, local trigger units, coincidence unit and event registration unit. Local trigger units form the trigger signal when the input signals according to certain conditions. These signals are sent to a coincidence unit, which determines what types of events should match for generating the main trigger. Event registration unit saves in the internal buffer memory information on the main trigger activation, such as a timestamp and the event type, and generates a signal that starts recording event in an array of ADCs. Upon request, the trigger system transmits information about the registered events from its buffer to the data acquisition system DAQ.

SPE counting was implemented by summing the number of pulses in a specified-width time window. The resulting sum is compared with the lower and upper thresholds for this type of event. There are two counting units for an independent pulse counting from upper and lower arrays of the PMT. The width of the time window and the thresholds are set in the registers of V1495 unit by the DAQ system. Functional diagram of the counting unit is shown in figure 2.

The circuit is clocked by the main generator of frequency 100 MHz. The signals from the discriminator (DI) fed to a parallel adder, which every 10 ns summarizes the values of all 19 inputs. Each sum is fed to the subtractor and FIFO, which promotes incoming value through all FIFO words. Thus, the delay time equal 10 ns* (capacity of FIFO). The value of a parallel adder is fed to the subtractor, where it is subtracted from the delayed value from the FIFO. The adder with accumulator summarizes the values obtained from the subtractor, which may be either positive or negative, and each clock cycle stores in the accumulator result being the current count of pulses in the time window.

Adjusting the width of the window is implemented as follows. The trigger system provides window width register in which the DAQ computer records the required value. Each clock cycle FIFO gives the number of used words (uw). This number is compared with that which is specified in the window width register, and in case of equality signal to read FIFO (RDreq) is issued.

The coincidence unit (figure 3) is implemented on the AND, OR, NOT logic elements. Bits of the channel enable register are set to 1 when the corresponding channels are enabled and for disabled channels bits are set to 0. The output of each local trigger and the output of the corresponding bit are fed to an OR gate with one NOT input. When enabled channels coincide, scheme & (AND)
generates signal to indicate a match. This signal enters the latch circuit for generating the output signal duration of 1 µs. The generated trigger signal passes through the circuit specifying the minimum interval between triggers, and if the interval is not violated, is issued to the ADC output array. The generation of the trigger can be disabled by sending signal to the external input inhibit. But event will be registered.

![Functional diagram of the coincidence unit.](image)

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Event registration unit is a circuit detecting the last arrived local trigger before the coincidence. The type of event is determined by number of channel from a local trigger arrived. The unit is provided with FIFO and time counter (24 bit width). Counter time must be tied to the DAQ time because of its overflow. FIFO depth is 4096 words (32 bit word width). Bits 31-28 are reserved, 27-24 - type of event code, 23-0 - time stamp of event in microseconds. The possibility not to generate the main trigger signal when FIFO overflows, or overwrite the oldest events was implemented.

4. Test results
Testing the SPE counting unit was carried out using arbitrary waveform generator, which are configured to generate pulses of known quantity. The maximum operating frequency of the system is 100 MHz, the maximum trigger delay after the appearance of the event is 10 ns. The circuit, part of the basis of the firmware for the on-board FPGA of CAEN V1495, occupied 50% of all its resources.

To test the system in the conditions close to the real, simplified model of one channel as part of installation (a photomultiplier in a dark box, the LED lighting it, and the discriminator) was assembled. The pulse of amplitude small enough so that the PMT can register single photoelectrons and 1 ms width was send from the signal generator to the LED. The average number of photoelectrons was varied by changing the amplitude of the supplied signal. The discriminator threshold was set at
0.5 SPE amplitude. The signal was fed to a discriminator FlashADC and was recorded in a file together with the sign of the trigger, the trigger was taken from the primary generator. Waveforms was analyzed further using a processing program that finds and counts the number of pulses in each event. Then the histogram distribution of the number of events by the number of pulses in the event for those events where there is a sign of the trigger, and for all events was drawn. The ratio of the histograms shows the efficiency shown in figure 4.

![Histograms](image)

**Figure 4.** The histograms for triggered events and for all events.

It is easy to see that the trigger is generated within strictly defined between the lower and upper thresholds (5 SPE and the SPE 16, respectively), while the efficiency is 100%. Operation of the trigger system was also tested in several data sets during a session of measurements carried out by the RED-1 detector (prototype of the RED-100 detector) in December 2013. By results of test defects are not found, the module operates normally.

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**References**

[1] Akimov D Yu *et al.* *arXiv:1310.0125*
[2] Akimov D Yu *et al.* 2013 *J. Instrum.* 8 P10023
[3] Chepel V and Araújo H 2013 *J. Instrum.* 8 R04001
[4] Akerib D S *et al.* 2014 *Phys. Rev. Lett.* **112** 9 091303
[5] Santos E *et al.* 2011 *J. High Energy Phys.* **1112** 115
[6] Akimov D Yu *et al.* 2012 *Instrum. Exp. Tech.* **55** 423