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Characterization of the low-background Hamamatsu R11410-20 cryogenic PMTs for the RED100 detector

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Abstract. The RED100 two-phase liquid xenon emission detector for neutrino coherent scattering experiments is equipped with 38 Hamamatsu R11410-20 photomultiplier tubes capable to operate at cryogenic temperatures and made of low background materials. A dedicated characterization procedure has been carried out for each PMT unit to be installed into the detector. The results presented here include single photoelectron analysis, gain curves for a wide range of the bias voltage values, data on dark count rate for 34 PMT samples. Peculiar noise characteristics of selected PMT units are analysed and discussed.

1. Introduction

The process of coherent elastic neutrino-nucleus scattering (CEvNS) was predicted by Standard model but has never been observed [1]. A broad experimental program aimed on study of this effect has been developed, utilizing different substances as working media, including the germanium detector technology [2], low-background CsI technology [3] and xenon emission detector technology, which was chosen by the RED collaboration [4] as the most relevant way to observe CEvNS.

For this purpose the RED100 two-phase cryogenic emission detector filled with ~200 kg of xenon has been developed and constructed at MEPhI to be irradiated by a pulsed neutrino beam at the Spallation Neutron Source (Oak Ridge National Laboratory, USA). An act of coherent neutrino scattering off Xe nucleus in the detector's volume leads to several keV of kinetic energy transfer to the Xe nucleus, causing a scintillation flash in the point of interaction and ionization electrons emission. Ionization electrons can be pulled up to a thin (~1 cm) Xe gas phase in the upper part of the detector with the help of a strong electric field (~500 V/cm) to be further accelerated there and generate an electroluminescent flash.

Light from the both signals is registered by two photodetecting arrays of 19 Hamamatsu R11410-20 photomultiplier tubes each. The tubes have been specially developed for their operation in low-background liquid xenon environments, including the optimization of their radiopurity, pressure-resistance and single photon response parameters. The main results of the these parameters check for

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first 34 PMTs installed in the RED100 detector are presented, and the observed deviations in the dark count rate of several PMT units are discussed.

2. Single photon response

Both scintillation and luminescent signals of interest in RED100 are rather faint (up to several hundreds of photoelectrons detected by all PMTs), that's why the knowledge of the PMTs' single photon detection capabilities is important. The LED-induced single photoelectron spectra have been measured for each PMT. The example spectra obtained for one of the PMTs for different bias voltages values are shown in figure 1.

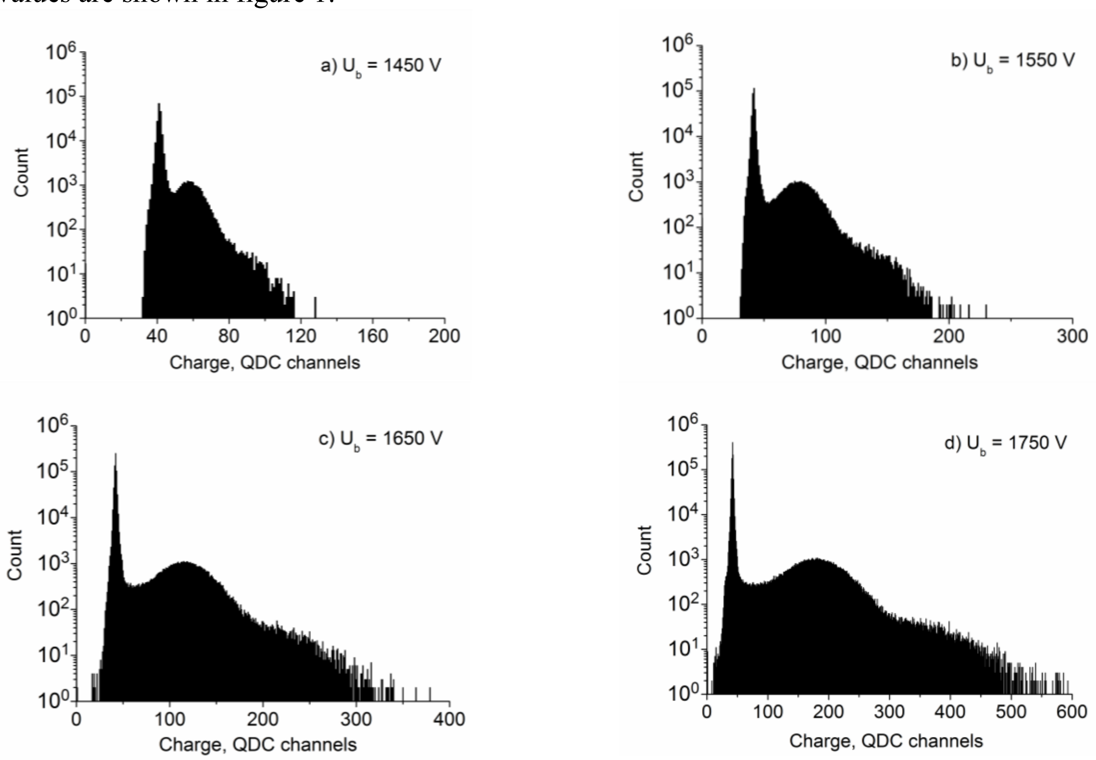

Figure 1. Typical LED-induced single photoelectron spectra, measured with one of the tested PMTs at different bias voltage values.

The "peak-to-valley" ratio is an important parameter of single photoelectron response of a PMT. It is calculated as the single photoelectron peak's maximum count divided by the minimum count in the "valley" between the peak and the pedestal. For the bias voltage values greater than 1500 V no significant difference could be seen in the peak-to-valley ratios of the obtained spectra, which are equal to ~3.7. For optimal bias voltage values, the smallest obtained peak-to-valley ratio for all the tested PMTs is 1.9, while 4.0 is the biggest one.

Once the single photoelectron spectra have been measured for different voltage values, it became possible to plot the distribution of dependencies of single photoelectron mean amplitude on the bias voltage values over all tested PMTs. The resulting plot is shown in figure 2.

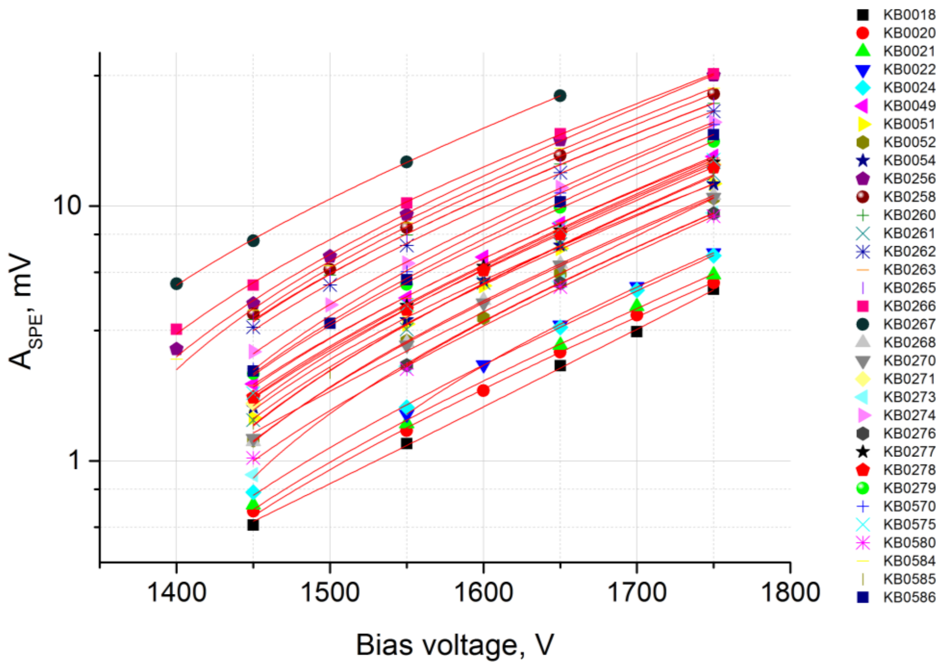

Figure 2. Dependencies of single photoelectron signals mean amplitude (A_{SPE}) on the bias voltage values over all the tested PMTs. Error bars lie within the data points size. Data points are connected using exponential fits (red solid curves).

This plot could help in gain-matching of all the PMTs used in the experiment, and also in setting the discriminator threshold at the level of 1/3 of single photoelectron amplitude while measuring the dark count rate values.

3. The dark count rate

Dark counts in a PMT are mainly caused by thermionic emission from the photocathode's surface [5], thereby having single photoelectron amplitude. Dark signals with greater amplitudes could be generated in a PMT in the processes of ion feedback, described in details for the Hamamatsu R11410-20 PMTs by reference [6]. The other way for large amplitude dark signals generation in a PMT is concluded in a charged particle penetration through the volume of a PMT window, which could lead to Cherenkov light emission. Combination of quartz window and VUV-sensitive photocathode in R11410-20 leads to very large amplitude (hundreds of photoelectrons) dark signals generation in case of atmospheric muons passing through the PMT's window [7].

Figure 3 represents the typical Hamamatsu R11410-20 PMT integral dark count rate amplitude spectrum measured by a scaler at different levels of discriminator's thresholds, confirming the predominance of dark pulses with single photoelectron amplitude.

Distribution of the gain-matched PMTs' dark count rates at discriminator threshold level of 1/3 of single photoelectron amplitude is shown in figure 4. The measurements were done in a light-tight metallic box (2 mm metal thickness) at room temperature after the PMT storage in darkness for at least 16 hours.

As one can see, the dark count rate values for the tested PMTs vary from several hundred hertz to ten kilohertz for almost all the tubes. Data points for the two tubes labeled KB0018 and KB0054 are not shown since dark count rate for these tubes is higher than 100 kHz. Additional studies, described in details here [8], have shown strong evidence of light emission from these PMTs' internal structure, causing these high values of "dark" count rates.

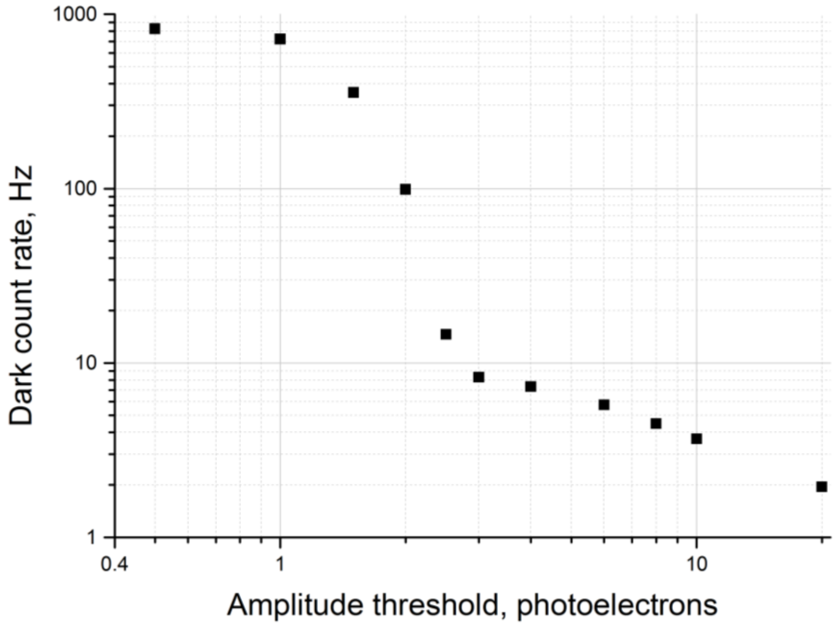

Figure 3. Distribution of dark count rate values measured at different amplitude thresholds. Error bars lie within the data points size.

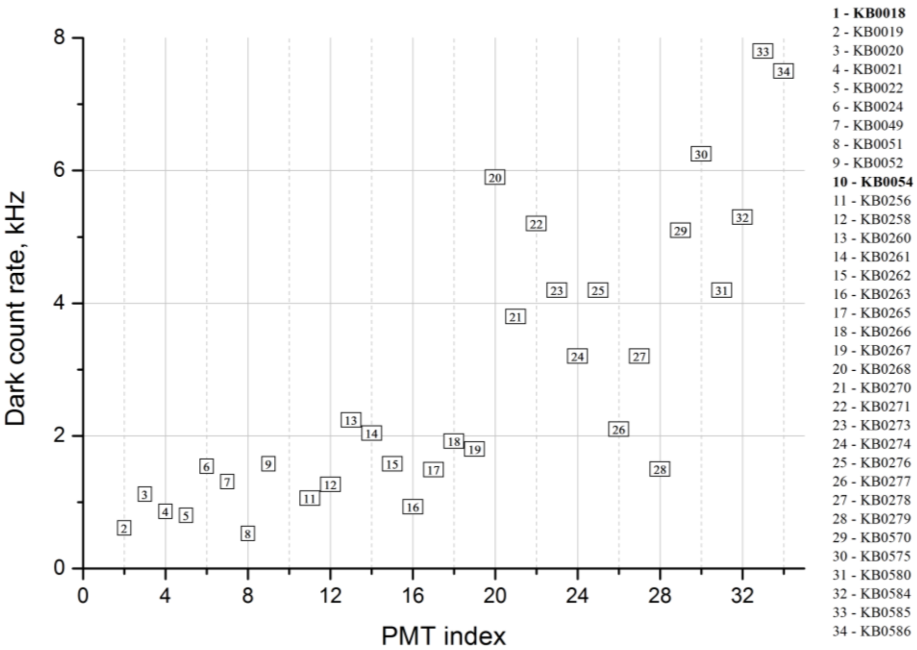

Figure 4. Distribution of the gain-matched ($8*10^6$ gain) PMTs' dark count rates at discriminator's threshold level of 1/3 of single photoelectron amplitude.

The light emission phenomenon is probably caused by specific constructive features of R11410-20 PMTs, concluded in the usage of non-widespread materials, determined by radiopurity reasons: quartz internal insulation, ceramic stem and Kovar metal body [9].

4. Conclusion

The study of the Hamamatsu R11410-20 PMTs parameters showed the propriety of the PMT choice for its use as a basic element of the RED100 photodetecting system due to an excellent single photon detection capability and acceptable noise parameters (for most part of the tested PMTs). It was shown that a predominant part of dark pulses in Hamamatsu R11410-20 is characterized by single photoelectron amplitude, which is consistent with the assumption of thermionic nature of major part of dark pulses in a PMT. At the same time, certain anomalies in the noise characteristics of several PMT units are described. These anomalies are associated with light emission from the PMTs' internal structure, which could be caused by a number of specific constructive features of these PMTs. The tested PMTs could be used in the RED100 detector after preliminary selection.

Acknowledgments

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