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МЕТОДИКА ФИЗИЧЕСКОГО ЭКСПЕРИМЕНТА

INVESTIGATION OF AVALANCHE PHOTODIODES RADIATION HARDNESS FOR BARYONIC MATTER STUDIES

V. Kushpil [a, 1], *V. Mikhaylov* [a, b, 2], *V. P. Ladygin* [c], *A. Kugler* [a],
S. Kushpil [a], *O. Svoboda* [a], *P. Tlustý* [a]

[a] Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež, Czech Republic
[b] Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Prague
[c] Joint Institute for Nuclear Research, Dubna

Modern avalanche photodiodes (APDs) with high gain are good device candidates for light readout from detectors applied in relativistic heavy-ion collision experiments. The results of the investigations of the APDs properties from Zecotek, Ketek, and Hamamatsu manufacturers after irradiation using secondary neutrons from U120M cyclotron facility at NPI of ASCR in Řež are presented. The results of the investigations can be used for the design of the detectors for the experiments at NICA and FAIR.

Современные лавинные фотодиоды (ЛФД) с высоким коэффициентом усиления являются хорошими кандидатами для считывания светового сигнала с детекторов, применяемых в экспериментах по релятивистским столкновениям тяжелых ионов. Представлены результаты исследований свойств ЛФД, изготовленных компаниями Zecotek, Ketek и Hamamatsu, после облучения вторичными нейтронами циклотрона U120M в ИЯФ АН ЧР (Ржеж). Результаты исследований могут быть использованы для проектирования детекторов для экспериментов коллабораций NICA и FAIR.

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INTRODUCTION

The studies of the properties of nuclear matter under extreme density and temperature conditions are the main subject of the relativistic heavy-ion collision experiments at Nuclotron-based Ion Collider fAcility (NICA) and at Facility for Antiproton and Ion Research (FAIR). The study of the dense baryonic matter at Nuclotron (BM@N project) [1] is proposed as a first stage in the heavy-ion program at NICA [2]. The research program of BM@N project includes the studies of the production of strange matter in heavy-ion collisions at beam energies between 2 and $6A$ GeV [3], in-medium effects for strange particles decaying in hadronic modes [4], hard probes and correlations [5], spin and polarization effects [6–8]. These studies will be complementary to the Compressed Baryonic Matter (CBM) project research program [9, 10] for fixed target heavy-ion collisions at FAIR in future.

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[1] E-mail: kushpil@ujf.cas.cz
[2] E-mail: mikhaylov@ujf.cas.cz

The main advantages of APDs are very compact sizes, low bias voltage, gain comparable to that for standard photomultiplier tubes (PMTs), relatively low price, insensitivity to magnetic field and absence of nuclear counter effect (due to the pixel structure). The APDs have the following typical properties: pixel density of about 10^4–$2 \cdot 10^4$ mm^{-2}, size of 3×3 mm^2, high dynamical range of 5–15000 p.e., photon detection efficiency of $\sim 15\%$, high counting rate of $\sim 10^5$ Hz.

The APDs are proposed as a main option for the light readout for Forward Wall Detector (FWD) at the BM@N [1] based on the high-granularity scintillation hodoscope. The FWD will allow one to measure the spectators and fragments for the precise reconstruction of the reaction plane in the semicentral events required for the measurements of flows, global polarizations of the hyperons, etc. The application of such a detector for heavy-ion collisions at HADES is described elsewhere [11]. Another application of APDs is the Projectile Spectator Detector (PSD) for the CBM setup. The PSD is a detector of noninteracting nucleons and fragments emitted at very low polar angles in forward direction in nucleus–nucleus collisions [12]. It will be used to determine the collision centrality and the orientation of an event plane. The PSD is a fully compensating modular lead/scintillator calorimeter, which provides very good and uniform energy resolution. The calorimeter comprises 44 individual modules, each consisting of 60 lead/scintillator layers with a cross section of 20×20 cm^2.

The radiation hardness of APDs, especially to neutrons, plays a significant role for the detectors placed in the forward direction. For instance, according to FLUKA simulation [13], neutron flux near the beam hole might achieve 10^{12} cm^{-2} for beam energy $4A$ GeV and 2 months of CBM run at the beam rate of 10^8 ions per second [12, 14]. In this paper, the results of radiation hardness of the APDs from Zecotek, Ketek, and Hamamatsu manufacturers to neutrons are presented. For the proposed experiments it is necessary to separate signal from noise for cosmic muons, while resolution of individual photons is not so important.

1. SETUP FOR NEUTRON IRRADIATION STUDIES

The APDs were irradiated using quasi-monoenergetic 35 MeV secondary neutron beam from U120M cyclotron facility at NPI of ASCR in Řež [15]. The schematic view of the setup for the beam fluence control and measurements of the irradiated APDs properties is presented in Fig. 1. It consists of PIN diode BPW34 connected to Kerma Meter RM-20 used for neutron fluence measurement [16], APD sample biased by voltage power supply from Keithley 6517A, APD tester [17] and Tektronix oscilloscope for online measurement of APD parameters, TCP-IP/GPIB and TCP-IP/RS-232 converters for the data transfer and experiment operation from the control room. The PIN diode BPW34 used for neutron flux measurement and APD sample are placed at the distance of ~ 3 m from the neutron source to achieve the minimal possible intensity of neutron beam for the irradiation. Other equipment is placed behind the concrete wall and connected by Ethernet to the computer in the control room.

Three types of APDs produced by Zecotek [18], Ketek [19], and Hamamatsu [20] were investigated to understand dependences of APDs radiation hardness on the manufacturing technology. These APDs were chosen as they are widely applied in nuclear and particle physics. The operational voltage and fluence equivalent to 1 MeV neutrons for these types of APDs are given in the Table.

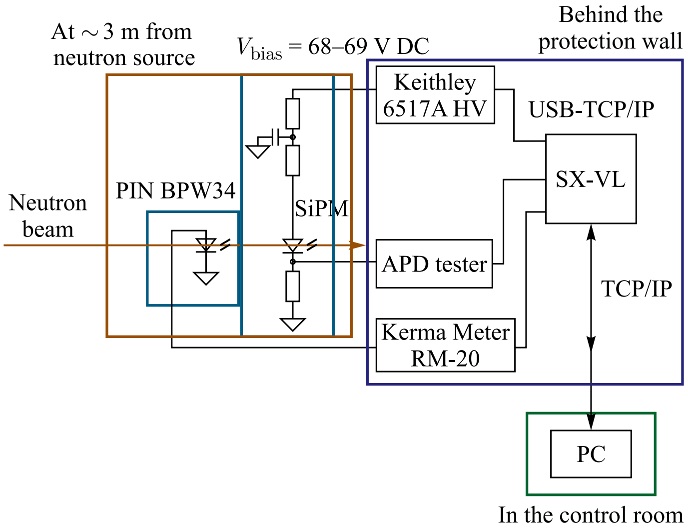

Fig. 1. Setup for the beam fluence control and measurements of the APDs properties

The operational voltage and 1 MeV neutron fluence for different irradiated APDs

APD type	Ref.	V_{bias}, V	1 MeV neutron fluence, cm^{-2}
Zecotek MAPD-3N	[18]	88.5	$(3.4 \pm 0.2) \cdot 10^{12}$
Ketek PM3350	[19]	23.5	$(2.5 \pm 0.2) \cdot 10^{12}$
Hamamatsu S12572-010P	[20]	69.2	$(6.5 \pm 0.6) \cdot 10^{10}$

Zecotek MAPD-3N, Ketek PM3350, and Hamamatsu S12572-010P were irradiated with the 1 MeV neutron doses of $(3.4 \pm 0.2) \cdot 10^{12}$ cm^{-2}, $(2.5 \pm 0.2) \cdot 10^{12}$ cm^{-2}, and $(6.5 \pm 0.6) \cdot 10^{10}$ cm^{-2}, respectively. Doses were measured by the special PIN diode calibrated for a 1 MeV neutron equivalent dose; the temperature during the irradiation and measurements was (22 ± 0.5) °C [16].

2. RESULTS FOR IRRADIATED APDs

The tests of APDs before and after irradiation were performed using the photons from Light Emitted Diode (LED) and cosmic muons. The LED allows one to investigate APD properties after irradiation in single-photon mode of operation when signal-to-noise ratio is very low, in particular, the threshold variation of APD photon detection. The cosmic rays provide the possibility to study APDs with minimal ionizing particles (MIPs).

For these purposes the experimental setup was arranged as shown in Fig. 2. The investigated APD was connected to the scintillators of one PSD module section [12] or to LED via the optical fibers. The cosmic muons penetrate the PSD scintillators with path length in the range of 16–200 mm depending on their declination angle. The coincidence of the signals from two scintillation counters placed upper and down the PSD module section provided a trigger for a DAQ system with frequency of about 10 counts per min. The Voltcraft

PPS-12008 power supply was used as a HV supply for the MAPD optical sensor. The signal from MAPD was processed by a fast amplifier and the resulting pulse-height distribution was collected by the Rohde & Schwarz RTO1024 oscilloscope with 2 GHz bandwidth.

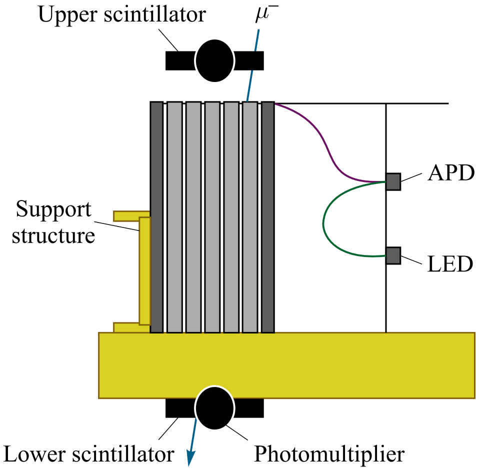

Fig. 2. Setup for the APDs tests with cosmic muons and LED

The APD characteristics were measured before and after irradiation. The Capacitance-Voltage (C-V), Current-Voltage (I-V), and Capacitance-Frequency (C-F) characteristics were studied using a dedicated testing setup at NPI in Řež [21]. After irradiation, the C-V technique showed significant decrease of hysteresis and fast but not complete self-annealing. The I-V curve revealed about 10^3 times increase of dark current after irradiation. The C-F study showed significant increase of short-living traps in silicon. The test results suggest an increase of internal APD noise, especially of the high frequency, which depends on the amount of short-living traps in the APD volume.

The results of the Zecotek MAPD-3N studies with LED and with cosmic muons are presented in Figs. 3 and 4, respectively. The dark and grey histograms represent the MAPD-3N amplitudes before and after irradiation, respectively. The solid lines are the results of the noise signal shape approximation after irradiation.

Figure 3 demonstrates clear single- and double-photon peaks before irradiation. After irradiation APD is unable to resolve single photons due to high noise level (∼ 10 p.e.). The amplitude from cosmic muons is defined by the PSD prototype design and efficiency of the light collection. Figure 4 shows that the averaged value of the signal amplitude from Zecotek

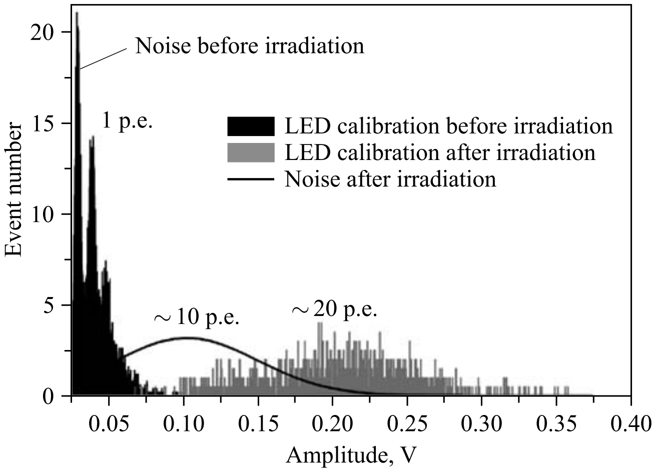

Fig. 3. Test results of Zecotek MAPD-3N with LED

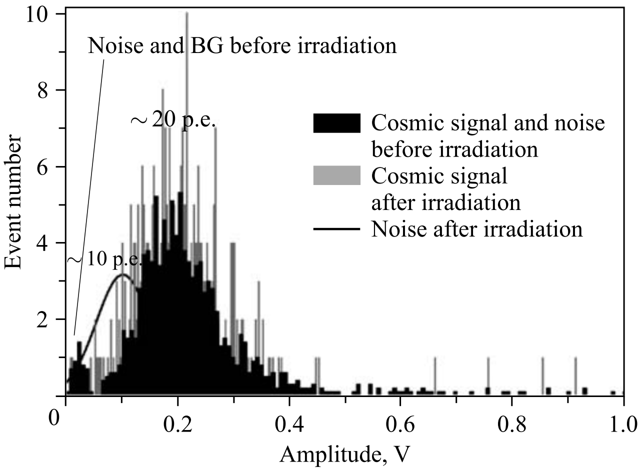

Fig. 4. Test results of Zecotek MAPD-3N with cosmic muons

MAPD-3N is ~ 0.2 V corresponding to ~ 20 p.e. The typical noise signal amplitude is ~ 3 p.e. and ~ 10 p.e. before and after irradiation, respectively. One can conclude that the signal from APD does not change drastically and it is still well separated from the noise after irradiation.

The results of the Ketek PM3350 studies with LED and with cosmic muons are shown in Figs. 5 and 6, respectively. The dark and grey histograms represent the PM3350 amplitudes before and after irradiation, respectively. The solid lines are the results of the noise signal shape approximation after irradiation.

The dark histogram shown in Fig. 5 demonstrates clear single- and double-photon peaks before irradiation. PM3350 after irradiation is unable to resolve single photons due to high noise level which is ~ 15 p.e. Figure 6 shows that the averaged value of the signal amplitude

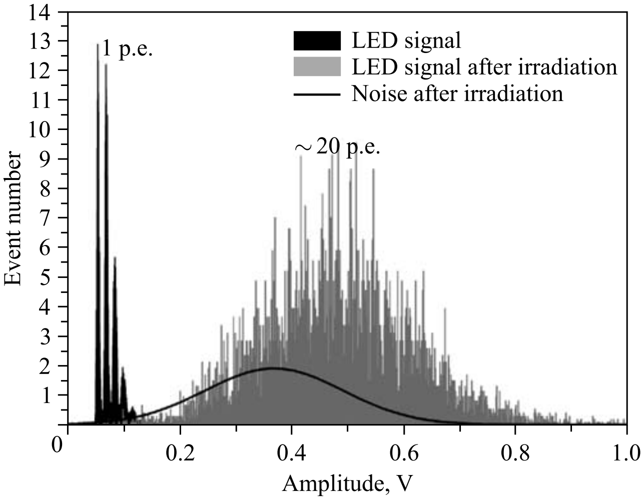

Fig. 5. Test results of Ketek PM3350 with LED

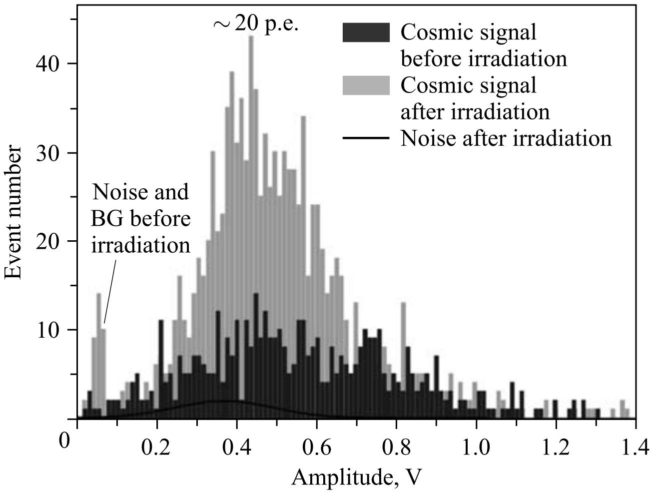

Fig. 6. Test results of Ketek PM3350 with cosmic muons

from Ketek PM3350 is ~0.4 V corresponding to ~20 p.e. The signal and noise peaks for irradiated Ketek PM3350 are very close, which makes signal from noise separation difficult.

The results of the Hamamatsu S12572-010P studies with LED are demonstrated in Fig. 7. The dark histogram and solid line represent the Hamamatsu S12572-010P amplitudes before and after irradiation, respectively. One can see good separation of the single-photon peak before irradiation. The averaged value of the signal amplitude from Hamamatsu S12572-010P after irradiation is ~0.18 V corresponding to ~26 p.e. It is well separated from the noise peak (~6 p.e.).

The Hamamatsu S12572-010P signal amplitudes obtained with cosmic muons are presented in Fig. 8. The dark and grey histograms represent the Hamamatsu S12572-010P amplitudes

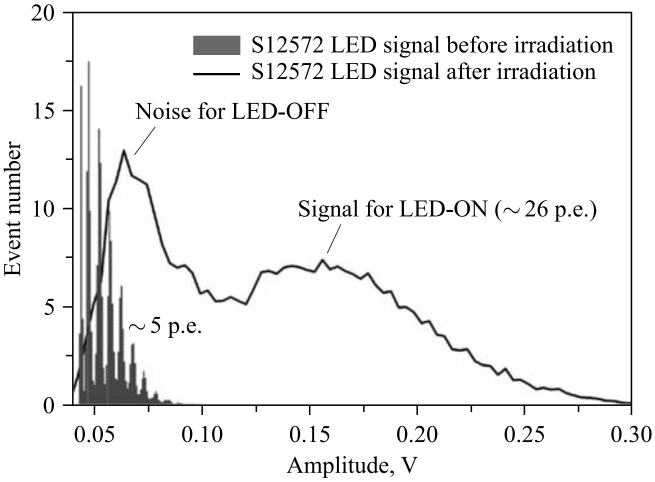

Fig. 7. Test results of Hamamatsu S12572-010P with LED

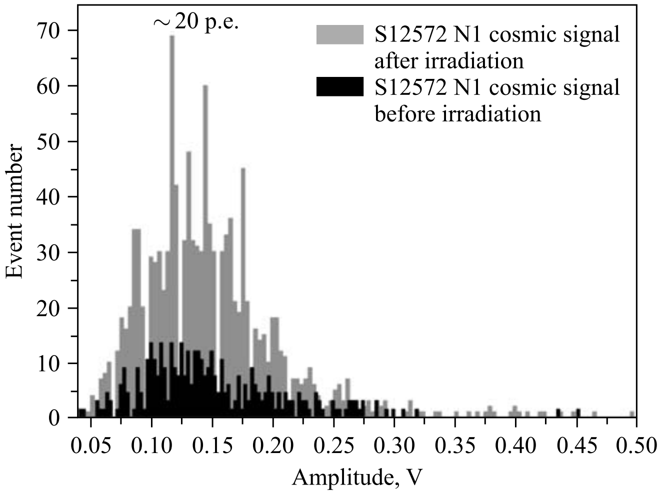

Fig. 8. Test results of Hamamatsu S12572-010P with cosmic muons

before and after irradiation, respectively. The averaged value of the signal amplitude from Hamamatsu S12572-010P is ~0.12 V corresponding to ~20 p.e. The signal from APD does not change drastically and it is still well separated from the noise after irradiation. However, one has to note that the neutron fluence for Hamamatsu S12572-010P was 30–50 times less than for Zecotek MAPD-3N and Ketek PM3350 (see the Table). It will be necessary to perform the studies for the APDs as a function of the irradiation dose.

CONCLUSIONS

- The studies of the Zecotek MAPD-3N [18], Ketek PM3350 [19], and Hamamatsu S12572-010P [20] properties have been performed before and after irradition by neutrons from U120M cyclotron facility at NPI of ASCR in Řež.
- It is demonstrated that the irradiation increases the APDs internal noise what leads to inability to detect single photons.
- It is shown that the signal and noise peaks are well separated for Zecotek MAPD-3N and Hamamatsu S12572-010P after irradiation. The Ketek PM3350 is unable to separate the noise and signal peaks for the current version of the PSD module.
- The obtained results are certainly important to design the detectors with APD light readout for FAIR and NICA experiments.
- The next steps will be a study of the radiation hardness of Ketek, Zecotek, and Hamamatsu APDs with online dose monitoring, long-time cosmic tests for all types of APDs, and investigation of dependence of optimal avalanche amplification on absorbed radiation dose.

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