1. INTRODUCTION

The studies of the properties of nuclear matter under extreme density and temperature conditions are the main subject of the relativistic heavy-ion collisions 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 6 A 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.

The main advantages of APDs are very compact sizes, low bias voltage, gain comparable to that for standard photo-multiplier tubes (PMTs), relative low price, insensitivity to magnetic field and absence of nuclear counter effect (due to the pixel structure). APDs have the following typical properties: pixel density about $10^4–2 \times 10^5$/mm$^2$, size of $3 \times 3$ mm$^2$, high dynamical range of $5–15000$ ph.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 from detectors applied in relativistic heavy ion collisions experiments. The results of the investigations of the APDs properties from Zecotek, Ketek and Hamamatsu manufacturers after irradiation using secondary neutrons from cyclotron facility U120M at NPI of ASCR in Úžice are presented. The results of the investigations can be used for the design of the detectors for the experiments at NICA and FAIR.

1 The article is published in the original.
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.

2. SETUP FOR NEUTRON IRRADIATION STUDIES

The APDs were irradiated using quasi-monoenergetic 35 MeV secondary neutron beam from cyclotron facility U120M 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 RM20 used for neutron fluence measurement [16], APD sample biased by voltage power supply from Keithley 6517A, APD tester [17] and Tektronix oscilloscope for on-line measurement of APD parameters, TCP-IP/GPIB and TCP-IP/RS-232 converters for the data transfer and experiment operation from the control room. PIN diode BPW34 used for neutron flux measurement and APD sample is 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 APD 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.

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

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

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

The tests of APDs before and after irradiation were performed using the photons from Light Emitting Diode (LED) and cosmic muons. LED allows 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 an optical fibers. The cosmic muons penetrate the PSD scintillators with path length in range 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 Voltechcraft PPS-12008 power supply was used as a HV supply for the MAPD optical sensor. The signal from the MAPD was processed by a fast amplifier and the resulting pulse-height distribution was collected by the Rohde & Schwarz RTQ1024 oscilloscope with 2 GHz bandwidth.

The APD characteristics were measured before and after the 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 Rez [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 Fig. 3 and Fig. 4, respectively. The dark and grey histograms represent the APD 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 photons 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 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 Fig. 5 and Fig. 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 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 the good separation of the single photon peak before the 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 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 table). It will be necessary to perform the studies for the APDs as a function of the irradiation dose.

4. CONCLUSIONS
—The studies of the Zecotek MAPD-3N [18], Ketek PM3350 [19] and Hamamatsu S12572-010P [20] properties have been performed before and after irradiation by neutrons from cyclotron facility U120M at NPI of ASCR in Rež.

—It is demonstrated that the irradiation increase 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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