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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Photomultipliers with microchannel plates

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Abstract

In this paper we present the results of tests of photomultiplier tubes with microchannel plates (MCP–PMT), which were manufactured at INP as prototypes for future use in particle detectors. The MCP–PMTs have smaller height/diameter ratio in comparison with ordinary PMTs, a gain of 10^4–10^7 and can operate in a magnetic field. Considerable degradation of the tubes occurs at about 0.01 C/cm^2 of collected anode charge. The PMT–MCPs show a clear single-electron peak. They were tested in setups with a quartz Cherenkov radiator and a NaI(Tl) scintillation crystal.

1. Introduction

Development of novel detectors for high luminosity colliders requires new types of photodetectors, which are compact, have a high gain and the ability to work in a magnetic field. A promising type of such photodetector is a microchannel plate photomultiplier (MCP–PMT), which has a broad spectrum of possible applications. MCP–PMTs are produced now by some manufacturers, e.g. Hamamatsu [1]. In Russia some experimental works were also reported [2].

Special features of MCP–PMTs are small transit time spread, which can be as low as 0.1 ns [3]; the ability to work in a magnetic field without dramatic loss of gain; compactness, which alone can be a reason for MCP–PMTs to compete with traditional PMTs; the ability to work in a single-electron mode. MCP–PMTs can be equipped with a position-sensitive multianode readout system with a rather good position resolution. Known drawbacks of MCP–PMTs are aging of the MCP, which leads to a gain degradation by 3–10 times for a total amount of charge passed through MCP of 0.1 C/cm^2 [4]; a long dead time reaching some ms per MCP channel [5], which may limit counting rate; and high price compared to traditional PMTs. MCP–PMTs are still not in use in particle detectors, but their employment in future detectors is being considered. For instance, the use of MCP–PMTs was proposed as a possible choice for fast time-of-flight scintillation counters for the KEK B-factory detector [6]. Multianode MCP devices might be suitable for scintillation and the wavelength shifting (WLS) fiber technique or Cherenkov ring image detectors. In many respects these photodetectors could compete with fine mesh PMTs [7] and hybrid phototubes with PIN or avalanche silicon diodes [8], which are also being developed for use in particle detectors.

Since 1985 work in the Novosibirsk Institute of Nuclear Physics (INP) has been carried out on the production of vacuum photodetectors for experiments on colliding beams machines. From the beginning two main technologies of PMT manufacturing were employed – the transfer method and the bulb technology. Up to now about 50 compact vacuum photodiodes [9] were manufactured using the transfer method, and a large number of about 5000 phototriodes [10] were produced, using the bulb technology for scintillation calorimeters of the SND [11], KEDR [12], and CMD-2 [13] detectors.

Some experimental setups, where compactness of photodetectors is crucial, also require high gain exceeding that of phototriodes, where it is about 10. For example, in a Cherenkov counter one has to detect with high efficiency light pulses of 10–100 photons of collected light. Taking into account quantum efficiency of a photocathode, a number of 1–10 photoelectrons can be expected. To detect such small signals, even using a slow low-noise amplifier with a typical effective noise charge of about 200 electrons, one has to use a photodetector with a minimum gain of 10^3. In this case MCP–PMT as such photodetector could be a good solution.

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Fig. 1. Photographs of PMTs with MCP, (a) NCT1 and NCT2, (b) NCT3.

For R&D purposes MCP–PMTs of two types were designed and manufactured in INP. The devices of the first type with one or two MCPs inside were produced using the bulb technology. They are named below as NCT1 and NCT2. A second type device (NCT3) was produced using the transfer method. The total number of the devices of each type was 3–5. Their characteristics and the results of their testing are described in the next sections.

Table 1
The principal parameters of MCP-MPTs

	NCT1	NCT2	NCT3
Envelope of PMT	Glass	Glass	Metal–ceramic
Window	UV-glass	UV-glass	Glass
Useful diameter [mm]	47	47	18
Photocathode	Sb–Na–K–Cs	Sb–Na–K–Cs	Sb–Na–K–Cs
Typical quantum efficiency at $\lambda = 410$ nm, [%]	10	10	15
Spectral range [nm]	250–800	250–800	350–800
Number of MCPs	1	2	1
Gain	5×10^3	10^7	10^4

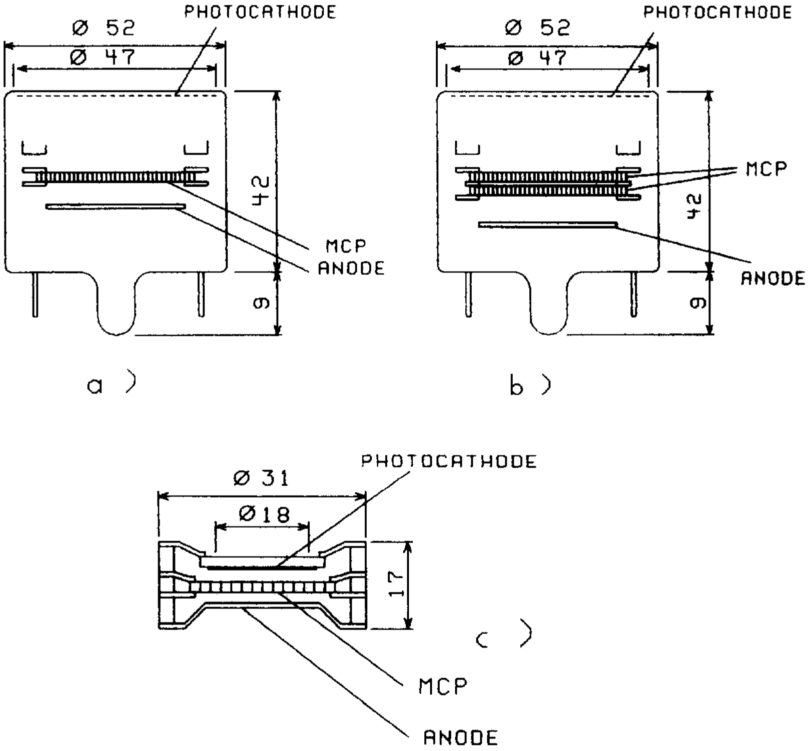

Fig. 2. Design and dimensions of PMTs with MCP, (a) NCT1, (b) NCT2, (c) NCT3. All dimenions are indicated in millimeters.

2. Photomultipliers NCT1 and NCT2.

These PMTs were produced using the conventional bulb technology. Both have all-glass packages. The shapes and dimensions of the devices are depicted in Figs. 1 and 2, and their main parameters are summarized in Table 1. Both PMTs have borosilicate glass windows and multialkali K–Na–Cs–Sb photocathodes with the maximum quantum efficiency of 10% at a wavelength of 410 nm. MCPs have a useful diameter of 32 mm, thickness of 0.5 mm, and channel diameter of 10 μm. Channels take up 65% of the total MCP's area, the resistance between MCP faces is 10^8 Ω. The saturation output current of MCP is estimated to be about 300 nA/cm^2. Voltages are applied to PMTs according to Figs. 3a and 3b.

For both devices the gain was measured by comparison

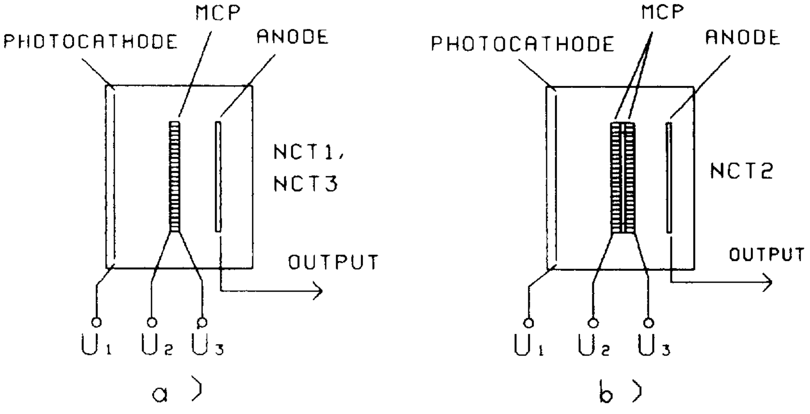

Fig. 3. A schematic of voltages applied to PMTs, (a) NCT1 and NCT3, (b) NCT2.

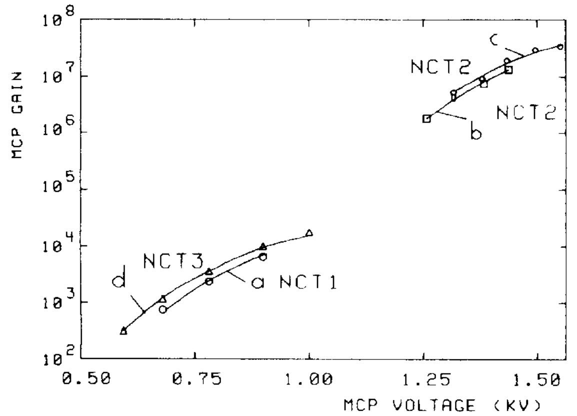

Fig. 4. MCP gain as a function of voltage applied to MCP, (a) gain of MCP NCT1, (b) gain of MCP NCT2, (c) gain of MCP NCT2, obtained from single electron spectrum, (d) gain of MCP NCT3, (for curves (a), (b) and (d) the gain was obtained by comparison between anode current and photocathode current).

of the photocathode current when PMT operated in photodiode mode at $U_2 = U_3 = 200$ V, with the anode current when all voltages were applied (see Fig. 3). A tungsten lamp with optical attenuating filters was used as a light source. Light attenuation was adjusted to produce the photocathode current of about 3×10^{-14} A. Dependence of PMT gain on voltage applied to MCP is shown in Fig. 4, curves (a) and (b). Fig. 5 represents dependence of PMT NCT1 output signal on the voltage between photocathode and MCP. The maximum gain for this tube was achieved at the voltage of 700 V.

The single-electron pulse height spectrum of PMT NCT2 was measured using attenuated light pulses from LED source (Fig. 6). Schematic of the setup for this measurement is shown in Fig. 7. The obtained spectrum shows an FWHM resolution of 110% and peak-valley ratio of 2.3 for single-electron peak. This measurement gives another method to determine MCP gain and compare it

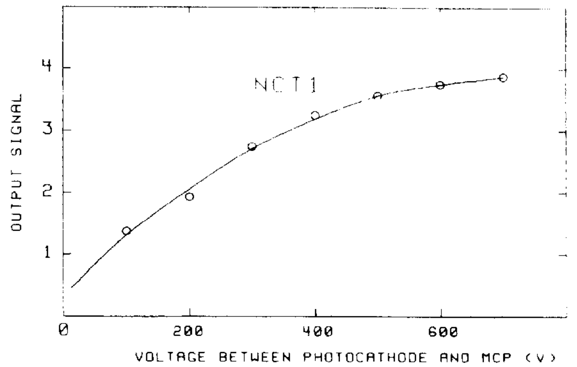

Fig. 5. PMT NCT1 output signal (arbitrary units) as a function of voltage between photocathode and MCP, MCP voltage is 950 V.

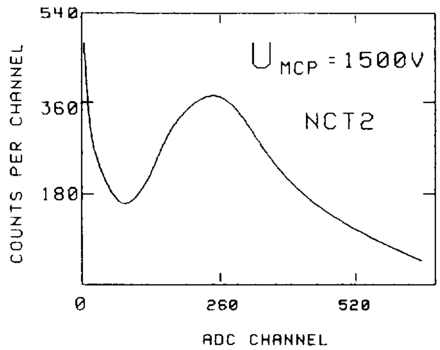

Fig. 6. Single-electron pulse height distribution for PMT NCT2.

with the value obtained previously for continuous illumination. An amplifier with the gain of 25, an integrator with the sensitivity of 0.73 mV/pC and ADC with the sensitivity of 0.25 mV per channel were used in this measurement. The total conversion coefficient of the channel was found to be 73 ADC channels per pC. Using this value and measured single-electron peak position (Fig. 6) the gain of MCP NCT2 was calculated. The result is shown as a function of MCP voltage in Fig. 4, curve (c). Observed difference of about 30% between curves (b) and (c) may be caused by calibration errors together with saturation effect in MCP channels.

Both types of PMTs were tested in a longitudinal magnetic field with LED light source illuminating central part of the photocathode. The output current was small, so PMT operated far from saturation. Measured data are plotted in Figs. 8a and 8b. The behaviour in a magnetic field of the PMTs NCT1, NCT2, and discussed in the next chapter NCT3 is similar to that observed in Ref. [14]. The plots show that PMTs can operate in a magnetic field up to 2.2 T. In the region up to 0.5 T the gain of PMT can even slightly increase.

PMTs NCT1 were also tested in a prototype Cherenkov counter. Schematic view of the counter is shown in Fig. 9. For triggering two scintillation counters were used with 10 cm lead absorber between them. As a Cherenkov radiator a

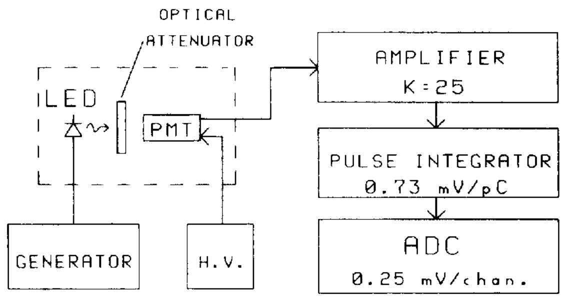

Fig. 7. The schematic of single-electron measurements with PMT NCT2.

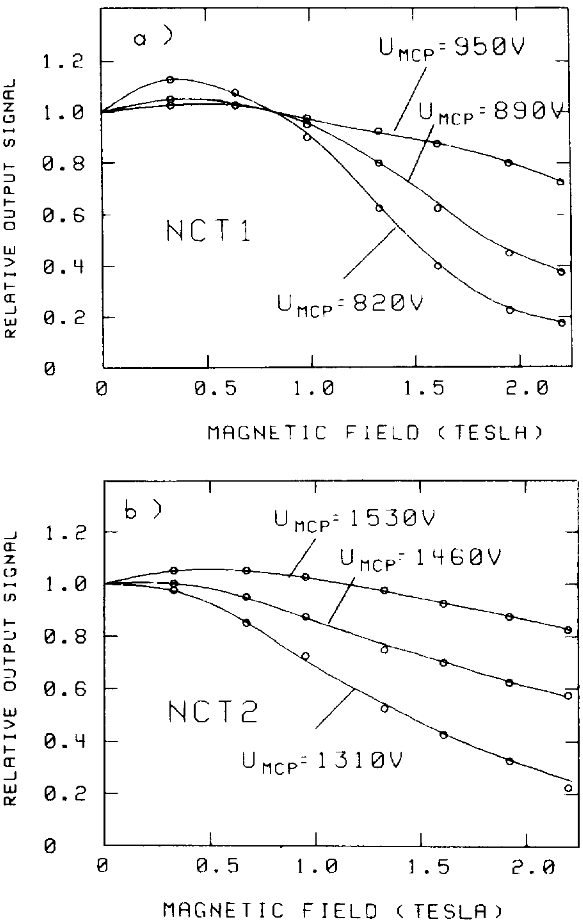

Fig. 8. PMT output signal versus strength of longitudinal magnetic field, (a) NCT1, (b) NCT2.

1 cm thick quartz plate optically coupled to the input window of PMT was used. Measurements of Cherenkov light output from cosmic muons gave an average number

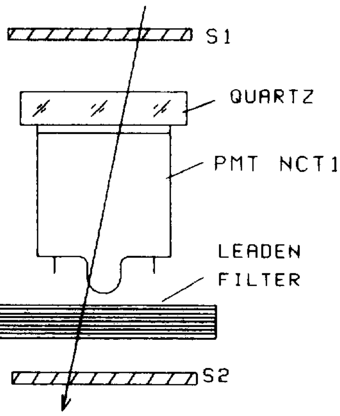

Fig. 9. Schematic of the prototype Cherenkov counter with PMT NCT2, tested with cosmic muons, S1, S2 – trigger counters.

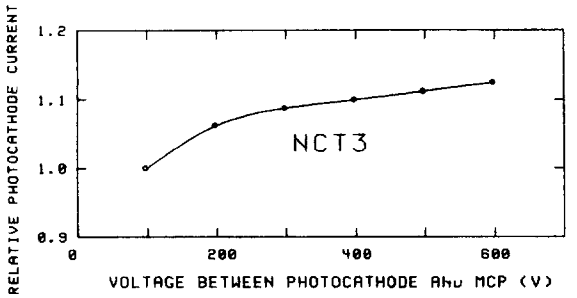

Fig. 10. Dependence of photocathode current of NCT3 on the voltage between photocathode and MCP plate, PMT operated in photodiode mode.

of 18 photoelectrons per particle crossing the quartz radiator. The result obtained shows the feasibility of using MCP-PMT in Cherenkov detectors.

2.1. Photomultiplier NCT3

For assembling of photodetectors by the transfer method the special high-vacuum setup [15] was built. In it the MCPs and other parts of PMTs were degassed, prefabricated photocathodes were extracted from glass containers and then PMTs were assembled using built-in manipulators. Shape and dimensions of the PMT are shown in Figs. 1 and 2, and some parameters are shown in Table 1. This PMT has a multialkali K–Na–Cs–Sb photocathode with the quantum efficiency of 15% at a wavelength of 410 nm. Inside PMT is placed an MCP plate with effective diameter of 23 mm and channel diameter of 10 μm.

The dependence of photocathode current on the voltage between photocathode and MCP was studied with LED light source (Fig. 10). The possible explanation of the photocathode current growth is the Schottky effect – the decrease of photocathode work function in a high electric field of about 10 kV/cm, because in planar design of NCT3 the distance between photocathode and MCP is only 0.5 mm.

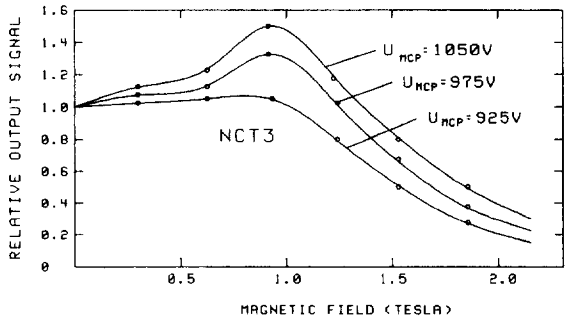

Fig. 11. Output signal of NCT3 versus strength of longitudinal magnetic field for different voltages applied to MCP.

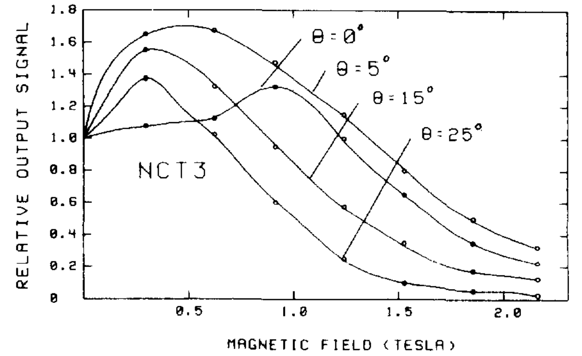

Fig. 12. Output signal of NCT3 versus strength of magnetic field for different angles between PMT axis and field direction.

The gain of this PMT was measured by comparing the anode current of PMT working in a photodiode mode with that in a PMT mode (Fig. 3a). The measurements were conducted with a tungsten lamp. Dependence of PMT gain on the voltage applied to MCP is shown in Fig. 4, curve (d). Unlike the case with NCT1, the MCP inside NCT3 was not affected by the alkali vapours during PMT manufacturing and, as one can see from Fig. 4, retains higher gain. Tests in a magnetic field included measurements of output signal on the field strength and direction (Figs. 11, 12, and 13). The remarkable feature of NCT3 is that due to its planar design the tube can operate at large angles up to 25° between PMT axis and field direction.

We studied the operation of a scintillation counter with NaI(Tl) crystal optically coupled with NCT3 and irradiated by a ^{137}Cs source. The measured width of the photoabsorption peak was about 8% FWHM (Fig. 14).

Another subject of interest was the long-term stability of MCP PMTs. To study degradation of NCT3 as a whole and MCP in particular, the measurements were carried out with continuous PMT illumination. The voltage and light intensity were chosen so, that initial gain of PMT was near

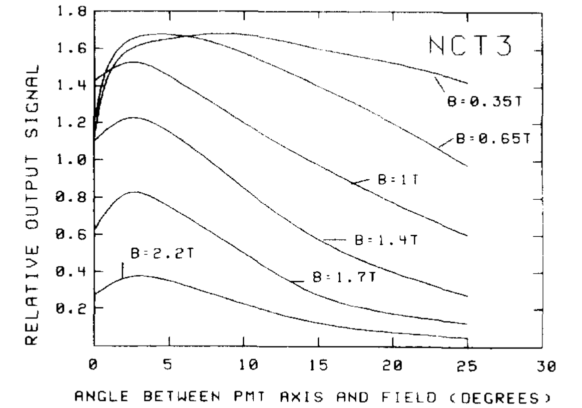

Fig. 13. Output signal of NCT3 versus angle between PMT axis and field direction for different values of magnetic field strength.

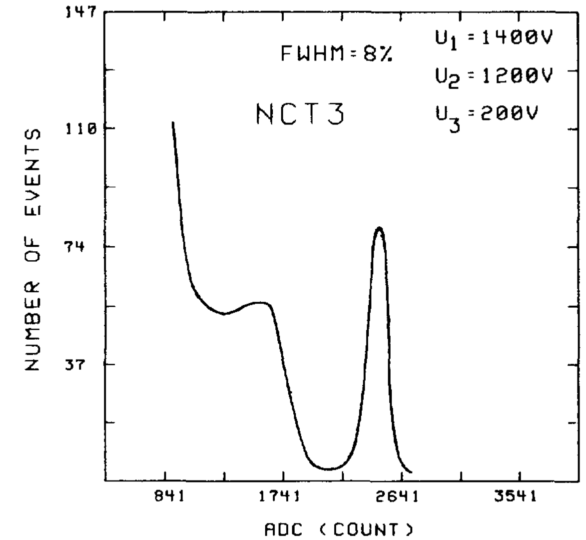

Fig. 14. Pulse height spectrum of PMT NCT3, coupled with NaI(Tl) crystal irradiated by 0.66 MeV ^{137}Cs source.

10^4 and the output current was 100 nA. A decrease of both MCP gain and photocathode quantum efficiency was observed. The latter is supposed to be caused by an ion bombardment of the photocathode mostly due to ionization of residual gas absorbed inside MCP channels. Considerable decrease of output signal occurs at the total output charge level of about 0.01 C/cm^2 of MCP. To reduce the photocathode damaging by ions it is possible to place a very thin "punch-through" aluminium film in front of the MCP. Comparison of gain degradation rate of MCP of NCT3 with MCPs of other manufacturers ([4,16]) is shown in Fig. 15. In spite of different production technologies of MCPs, the curves in Fig. 15 show similar behaviour. We can conclude that for applications with low mean anode current the degradation problem is not crucial. Besides, for

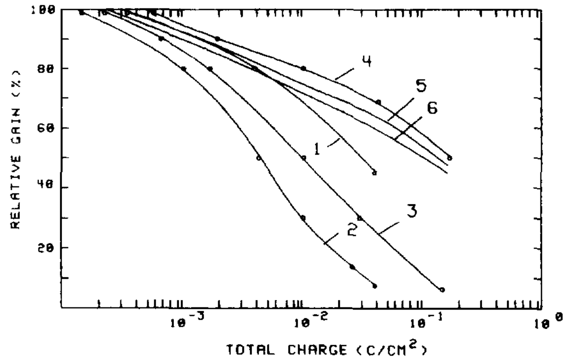

Fig. 15. Degradation of NCT3 and its MCP together with MCPs of other manufacturers versus total anode charge, 1 – gain degradation of NCT3, 2 – output signal degradation of NCT3, 3 – gain of an "old" MCPs [4] of Hamamatsu, 4 – gain of the "new" MCP [4] of Hamamatsu, 5 – gain of Mullard MCPs [16], 6 – gain of Galileo MCPs [16].

some applications it would be possible to recover gain of MCP applying higher voltage.

3. Conclusion

In the Institute of Nuclear Physics, Novosibirsk, several MCP–PMTs of three types were manufactured in the frame of R&D work for future collider detectors. Two of them have a diameter of 52 and 50 mm height and are equipped with one or two MCPs. The third, a proximity type device with one MCP, has a diameter of 31 mm and height of 17 mm.

Results of measurements with produced samples of MCP–PMTs allow to conclude, that the devices have a quantum efficiency of 10–15%, an internal gain of 10^4–10^7, and tolerance to magnetic field up to 2.2 T. MCP–PMTs are able to operate in a single electron mode. The tests show their ability to work in Cherenkov and scintillation counters instead of ordinary PMTs. The considerable degradation of MCPs occurs when a total charge passed through MCP exceeds 0.01 C/cm^2.

The MCP–PMTs are expected to have high time resolution. Multianode position-sensitive MCP–PMTs can be of interest for applications where scintillating and wavelength shifter fibers are used. The employment of such MCP–PMTs can considerably improve the quality of particle detectors where the mentioned above properties are important.

Acknowledgements

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