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Extending the dynamic range of the 2-inch-diameter PMT for the ALPACA experiment

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The ALPACA experiment aims to observe sub-PeV gamma rays in the southern hemisphere with a new air-shower-array observatory. The observatory is located at an altitude of 4,740 m above sea level on Mt. Chacaltaya, Bolivia. A new surface air shower array plans to consist of 401 scintillation detectors covering an 83,000 m^2 surface area. Each scintillation detector is equipped with a 2-inch-diameter photomultiplier tube (2-inch PMT). The 2-inch PMTs detect the scintillation light produced by shower particles passing through the plastic scintillators and reconstruct the energies and directions of gamma rays and cosmic rays. In this paper, the extension of the maximum measurable number of particles within the linearity range of the PMT, the so-called dynamic range, is studied by reading out (electronic) signals from one of the dynodes of the PMT. As a means of extension, in addition to the normal anode signal, the signal is read out from the dynode, which is in the middle of signal amplification. Our results show that the 2-inch PMT, R7724, produced by Hamamatsu Photonics has achieved a dynamic range of about 500 particles with dynode readout from the seventh of a total of ten dynodes. This enables the accurate determination of the energies of gamma rays up to about 2 PeV.

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1. Introduction

Galactic accelerators of PeV charged cosmic rays, the so-called PeVatrons, are the biggest targets of cosmic-ray physics. Since it is not appropriate to observe cosmic rays to identify PeVatrons due to the bend of their trajectories by the Galactic magnetic field, the PeVatron search can be performed by observing gamma rays in the 100 TeV region (sub-PeV), which are produced from the decay of neutral pions generated through collisions between the cosmic rays and the interstellar matters around sources.

Although numerous PeVatron candidate objects, including galactic centers, have been reported in the southern sky, sub-PeV gamma-ray observations are largely unexplored. Therefore, the ALPACA experiment aims to pioneer sub-PeV gamma-ray astronomy in the southern sky by installing an instrument on Mount Chacaltaya in Bolivia in the southern hemisphere. The instrument consists of two parts: a surface air shower array and an underground muon observatory. The surface air shower array consists of a total of 401 surface scintillation detectors spaced 15 m apart. Each surface scintillation detector is equipped with a photomultiplier tube (PMT) to capture the scintillation light produced by the passage of air shower particles.

In order to identify the source, it is necessary to determine the maximum acceleration energy of cosmic rays from gamma-ray spectra with high accuracy. Therefore, it is important to extend the maximum number of particles that can be measured without underestimation (dynamic range) per surface scintillation detector. In the preceding Tibet ASg experiment in the Northern Hemisphere, the dynamic range was extended by using two types of photomultiplier tubes with different amplification factors. The goal of this study is to extend the dynamic range of the 2-inch diameter PMT (2-inch PMT), which is planned to be used as the surface scintillation detector for the ALPACA experiment, so that one PMT per detector will be sufficient to observe the ALPACA experiment.

2. Required peformance of PMTs for surface detectors

Figure 1 is the lateral distribution of air showers produced by gamma rays, where the horizontal axis is the distance from the core position of the shower and the vertical axis is the number of particles per square meter (particle number density). We don't use the data within 10 m from the core position in the analysis because the number of surface scintillation detectors is small and the particle number density fluctuates greatly due to errors in determining the core position. Therefore, focusing on the data at a distance of more than 10 m, the number density of particles in the shower produced by gamma rays of 1 PeV is less than 1,000 particles at the maximum. This means that if the dynamic range is up to 1,000 particles, the shower produced by 1 PeV gamma rays can be sufficiently detected without underestimmating the number of particles.

3. Study of dynamic-range extension

3.1 Design of PMT-voltage divider

The voltage divider for R7724 created in this study are shown in Figure 2, 3. The following two methods of extending the dynamic range were implemented.

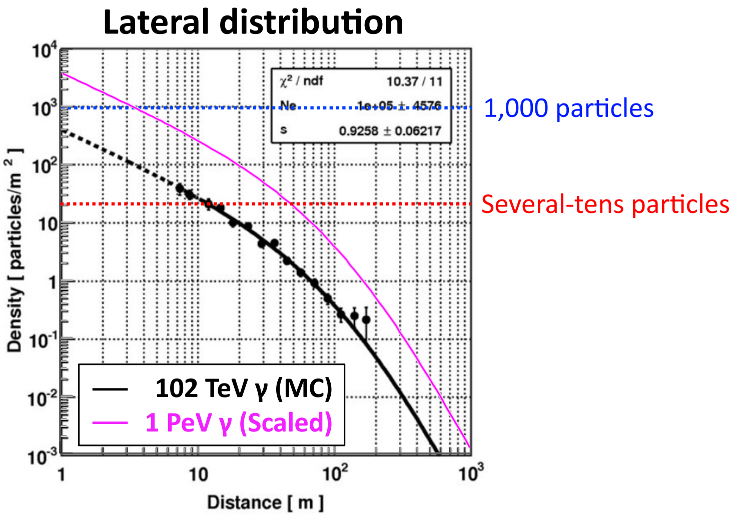

Figure 1: Lateral distribution of showers produced by 102 TeV and 1 PeV gamma rays[1]. The black dots are the results of Monte Carlo simulations for 102 TeV gamma rays. The solid black line is the NKG function fitted to the data for the distance over 10 m, and the dashed black line is the extrapolation of the fitted NKG function for the distance within 10 m. The solid magenta line representing the 1 PeV gamma ray is the black dashed line multiplied by 10 on the vertical axis.

3.1.1 Dynode readout

Dynode readout is the operation of reading out the signal from the dynode, which is in the process of amplifying the signal, in addition to the signal from the anode normally used in the operation of the photomultiplier tube. The dynamic range is qualitatively expected to be extended. In a previous study of dynode readout[2], the dynamic range was extended from 1,350 photoelectrons to 4,000 photoelectrons by performing dynode readout from the seventh stage of the photomultiplier tube R5912, which also has 10 dynode stages. In this paper, the readout was performed from the seventh stage in reference to this paper.

3.1.2 Tapered divider

The ratios of the voltage across the dynodes (voltage divider ratios) for the normal and tapered dividers are shown in Table 1 The normal divider is a circuit fabricated with reference to the voltage divider ratios provided by Hamamatsu Photonics. The normal divider is a circuit fabricated with reference to the voltage divider ratios provided by Hamamatsu Photonics, and is characterized by the fact that the voltage divider ratios are designed to be relatively evenly spaced. On the other hand, the tapered divider is a circuit developed in this paper, and is designed so that the voltage divider ratio increases in the latter stages. The purpose of this is to suppress the space-charge effect by increasing the voltage of the latter stage, which is strongly affected by the space-charge effect. This is expected to improve the linearity of both the anode and dynode signals, leading to an extended dynamic range. The disadvantage of the tapered divider is that the amplification of the number of electrons in the first stage is smaller than that of the normal divider, and the gain is expected to decrease as a result.

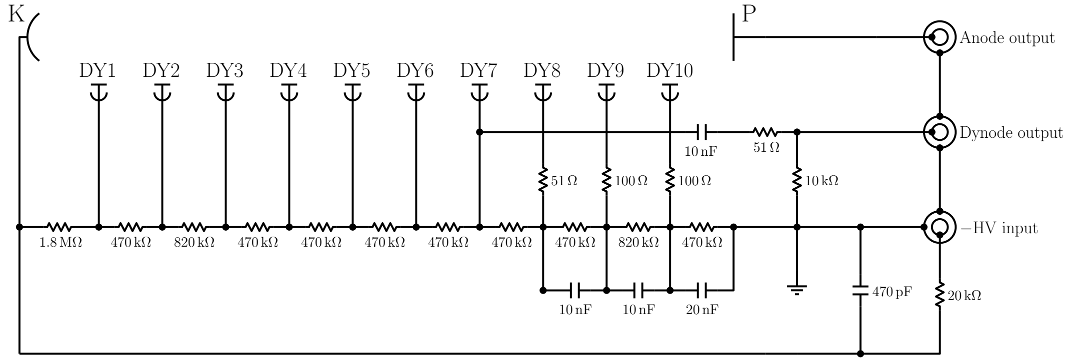

Figure 2: Normal divider

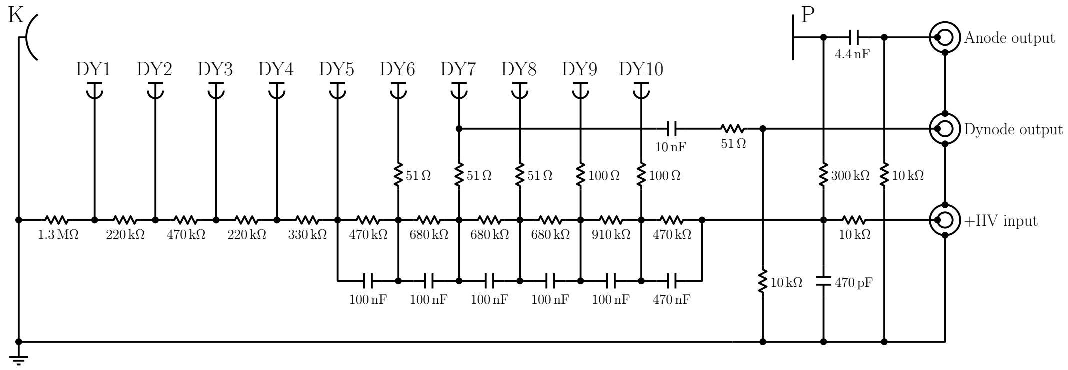

Figure 3: Tapered divider

3.2 Results

The dynamic range of the normal divider and the tapered divider was measured when 1750 V and 2000 V were applied, respectively. As a result, the dynamic range extended to about 500 particles when 1750 V was applied to the normal divider. In this case, focusing on the lateral distribution for the distance over 10 m (show Figure 1), it can be seen that about 500 particles correspond to approximately 2 PeV energies of gamma rays. It indicates that gamma rays up to 2 PeV can be detected without underestimations of the number of particles. The dynamic range after the extension fully meets the requirements of ALPACA experiment for observations of sub-PeV-gamma rays.

4. Summary

ALPACA aims to observe sub-PeV gamma-rays in the southern sky. Target dynamic range of up to 1,000 particles (a few PeV) per surface scintillation detector. Attempted to extend dynamic range of 2-inch PMT, R7724 by anode/7th-dynode readouts with normal/tapered dividers. As a result, Dynamic range extended up to about 500 particles (~ 2 PeV) with 7th-dynode readout of the normal divider, which sufficiently agrees the requirement of ALPACA experiment.

Table 1: The voltage divider ratio of the normal divider and the tapered divider. The total resistance is 7.20 MΩ and 6.43 MΩ for the normal and tapered dividers, respectively. The designed ratios are the ratios calculated according to the catalog values of the resistors. The measured ratio is the value obtained by measuring the voltage across the dynodes with a tester while 10 V is applied to the circuit, and normalizing the total voltage value to 100.

Normal divider

Electrode	K	DY1	DY2	DY3	DY4	DY5	DY6	DY7	DY8	DY9	DY10	P
Designed ratio	25.0	6.53	11.4	6.53	6.53	6.53	6.53	6.53	6.53	11.4	6.53	
Measured ratio	23.7	6.67	11.4	6.67	6.66	6.68	6.67	6.67	6.67	11.4	6.71	

Tapered divider

Electrode	K	DY1	DY2	DY3	DY4	DY5	DY6	DY7	DY8	DY9	DY10	P
Designed ratio	20.2	3.42	7.31	3.42	5.13	7.31	10.6	10.6	10.6	14.2	7.31	
Measured ratio	19.4	3.56	7.41	3.57	5.31	7.41	10.6	10.6	10.6	14.0	7.42	

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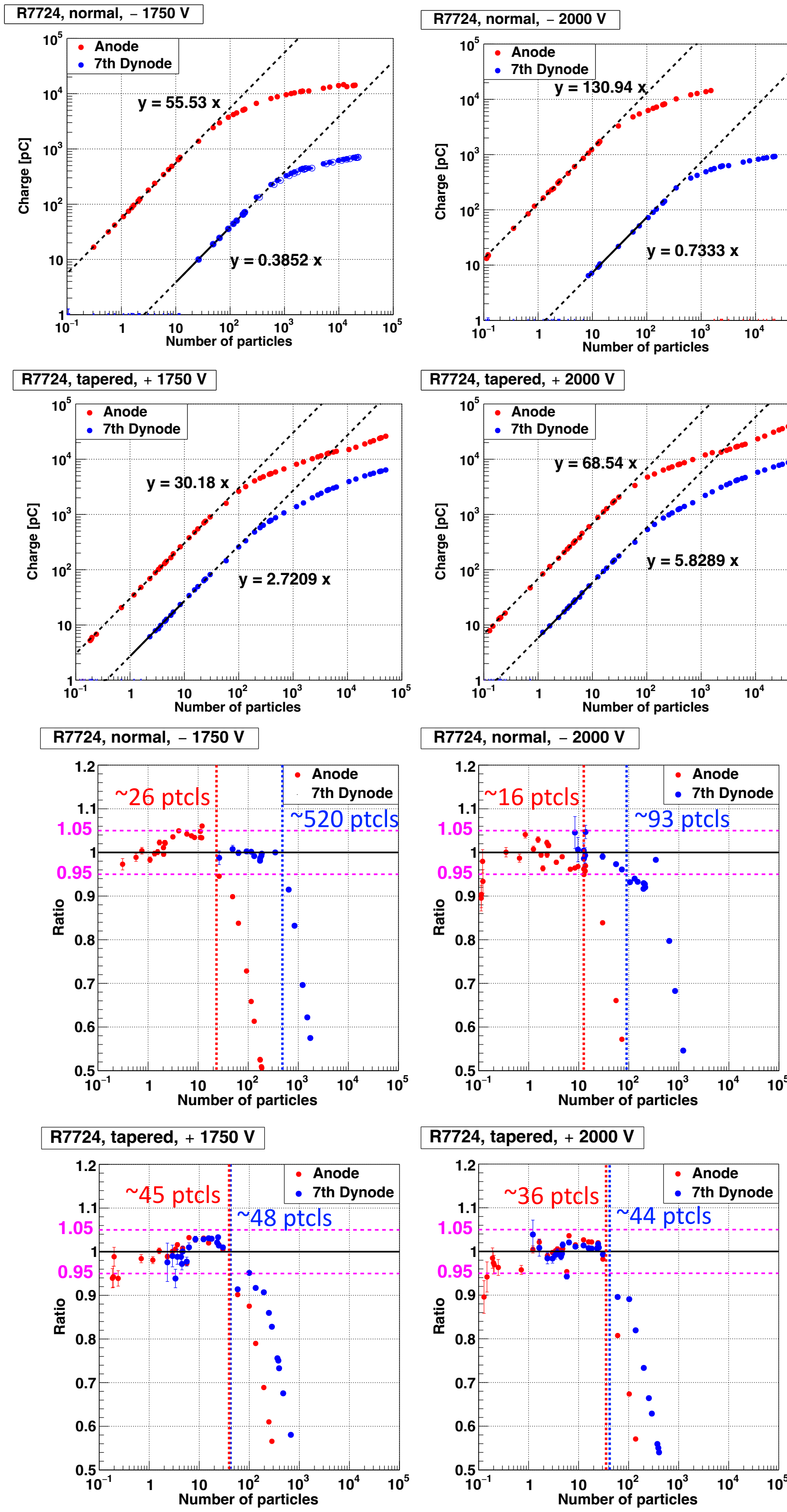

Figure 4: Measurement results of the dynamic range of 2-inch PMT, R7724.

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