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A large dynamic range readout design for the plastic scintillator detector of DAMPE

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ABSTRACT

A large dynamic range is required by the Plastic Scintillator Detector (PSD) of DArk Matter Particle Explorer (DAMPE) to detect particles from electron to heavy ions with $Z \leq 20$. To expand the dynamic range, the readout design based on the double-dynodes signal extraction from the photomultiplier tube has been proposed and adopted by PSD. To verify this design, a prototype detector module has been constructed and tested with cosmic ray and relativistic ion beam. The results match with the estimation and the readout unit could easily cover the required dynamic range of about 4 orders of magnitude.

1. Introduction

DArk Matter Particle Explorer (DAMPE) is a satellite-borne particle detector aiming for in-direct dark matter search, high-energy gamma astronomy and primary cosmic ray studies [1]. It is designed to cover a wide energy range from 5 GeV to 10 TeV for electrons and photons and from 10 GeV to 1 PeV for heavy ions, with unprecedented resolution (1.5% for 100 GeV electrons).

The Plastic Scintillator Detector (PSD), located at the top of the satellite, is a key component of DAMPE. It consists of two layers of plastic scintillator bars which are orthogonal to each other, and covers an effective area of 820 mm × 820 mm. The bars are made of EJ-200 [2], with the dimension of 884 mm × 28 mm × 10 mm. Each bar is readout at both ends by the Hamamatsu R4443 photomultiplier tube (PMT), which is a low noise PMT ruggedized for space usage [3]. The EJ-560 [2] optical pads are used as the coupling material between the bar end and the PMT to assure the proper transmission of the scintillation light as well as to avoid the hard contact between them.

By measuring the deposited energy, PSD serves as an anti-coincidence detector for e/γ discrimination as well as a charge detector for heavy ions up to $Z=20$. As the deposited energy of the charged particle in PSD is approximately proportional to Z^2, this implies a wide range of output signal amplitudes and requires a large dynamic range design for the PSD readout unit. On the other hand, the available weight and power on the satellite are limited and this imposes a constraint in the selection of the electronic components of the readout unit.

In this paper, the readout design of PSD with large dynamic range and low power consumption is reported. An estimation of the dynamic range needed by PSD is presented in Section 2. The readout scheme is determined based on this estimation, and the detailed design process and the composition of the readout unit are described in Section 3. Verification tests for the dynamic range have also been carried out on a prototype detector module using cosmic ray and relativistic heavy ion beam and the test results are discussed in Section 4.

2. Dynamic range requirement

The dynamic range requirement for the PSD readout unit is affected by many different factors. To make things more clear, we define the mean light yield produced by a singly charged minimum ionizing particle penetrating vertically through the center of the PSD bar as one MIP, and use it as the unit for the dynamic range estimation.

The light yield of the plastic scintillator in response to different charged particles forms the basis for the dynamic range

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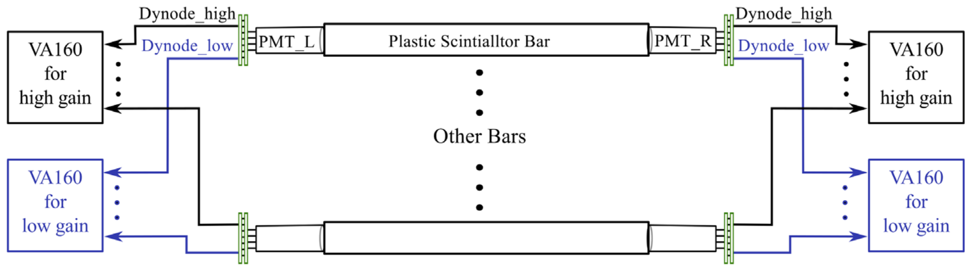

Fig. 1. PSD readout scheme with two measurement ranges.

estimation. Due to the quenching effect, the scintillation efficiency of organic scintillator is not a constant, but a nonlinear function of the energy loss dE/dx, which can be described empirically by the Birks' law [4]. However, for heavy ions in the relativistic region, the scintillation mechanism is much more complicated and the Birks' law fails to apply directly. Several modified models [5–8] have been proposed to extend the Birks' law, nevertheless large discrepancy exists between them when extrapolating to the high-Z nuclides. Due to these theoretical difficulties, our estimation of the light yield is based on the relativistic heavy ion beam test result of AMS-02 TOF detector [9,10], which also uses EJ-200 with the same thickness as the detection material. According to the parameters from [9], the light output of calcium ($Z=20$) is about 270 times larger than that of proton ($Z=1$). As all singly charged minimum ionization particles have approximately the same energy loss in the PSD bar, they have approximately the same light output as well. Thus, the mean light yield of the PSD bar in response to all the charged particle species covered by PSD ranges from 1 MIPs to 270 MIPs.

The mean light yield is also related to the traversing length of the incident particle in the PSD bar. DAMPE is designed to cover a broad field view, which demands the maximum incidence angle to be $\pm 60°$. Thus, the maximum traversing length is twice that of the normal incidence case. This in turn doubles the energy loss as well as the light yield and extends the maximum mean light yield to 540 MIPs.

Both the process of energy loss in the plastic scintillator and the associated scintillation are intrinsically random, leading to the light yield fluctuation. The light yield fluctuation follows the Gaussian distribution and also contributes to the dynamic range requirement. Assuming the standard deviation (σ) of the fluctuation is 10% and 5σ is adopted for the full coverage, then the upper limit of the light yield extends to 675 MIPs and the lower limit reduces to 0.75 MIPs.

The scintillation photons produced at the hit position are transmitted to the bar end undergoing a series of reflection, absorption and refraction. To improve the reflection efficiency, the PSD bars are surface polished and wrapped by the Tyvek paper [11]. However, the length of the PSD bar is so long that the light attenuation during the transmission process cannot be ignored, and this extends the dynamic range tremendously. A preliminary test shows that the light attenuation ratio from the center to the end of the bar can be well controlled above 50%. Thus, the output light collected by the PMT at the bar end shall vary between 0.375 MIPs and 1350 MIPs.

Finally, to ensure the clear separation of the smallest signal from the electronic noise as well as to leave some redundancy for the adjustment, the dynamic range requirement for the readout unit of PSD is determined to be 0.1–1400 MIPs.

3. Design of the readout unit

3.1. Readout scheme

An application specific integrated circuit VA160, developed by IDEAS Inc. [12], is adopted as the charge measurement circuit of PSD. VA160 is a low power and radiation harden chip designed specifically for the DAMPE project, and is optimized for positive input charge with a dynamic range from -3 pC to 13 pC. It has 32 input channels, and each channel has a full chain of charge sensitive pre-amplifier, CR-RC shaping amplifier and sample-hold circuit for independent charge measurement.

To cover the required dynamic range of about 4 orders of magnitude, it is found that a single VA160 channel is not sufficient. Thus, the readout scheme which uses a PMT with double-dynodes signal extraction and connects the output signals to separate VA160 channels has been proposed and adopted for the readout system of PSD. Two measurement ranges can be achieved in this way, with the high-gain dynode channel for small light output measurement and the low-gain dynode channel for large light output measurement. To reduce the crosstalk between th low-gain and high-gain channels, signals from the two dynodes are connected to different VA160 chips as shown in Fig. 1.

The front-end electronic (FEE) board based on VA160 has been developed and fully tested by the PSD group [13]. The analog to digital conversion is performed by a 14-bit ADC. The test result [13] shows that a linear range up to 12 pC is guaranteed for each FEE channel and the input noise level (σ) of the whole PSD readout channel is expected to be smaller than 6 fC. This implies that the response of 0.1 MIPs shall be larger than 30 fC as a 5σ separation is required, i.e. $1\ \text{MIP} \geq 300\ \text{fC}$. Thus the dynamic range from 0.1 MIPs to 40 MIPs can be covered by the high-gain dynode channel, and the remaining range shall be covered by the low-gain dynode channel. This constrains the gain ratio between the two dynode stages to be ≥ 35.

3.2. Selection of the dynode stages

To select the appropriate dynode stages for signal extraction, a rough estimation of the mean number of photon electrons (PE) generated by one MIP in the center of the bar is carried out.

The mean energy deposit of the singly charged minimum ionizing particle in a 10 mm plastic scintillator is about 2 MeV [14], and the scintillation efficiency of EJ-200 is 10^4 photons/MeV [2]. The scintillation photons are emitted isotropically in all directions. Thus, half of these photons points to one end of the bar and the other half points to the other end. However, due to the refraction on the boundary, only 22.5% of them are within the total reflection angle and will undergo the transmission process to the end of the bar. The number of photon electrons is then deduced as follows: