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A Method of Alignment for Plastic Scintillator Detector of DAMPE

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DArk Matter Particle Explorer (DAMPE, also known as Wukong) is a satellite-borne high-energy particle detector launched on December 17th, 2015. DAMPE focuses on the indirect detection of dark matter and the study of high-energy astrophysics by means of spectral measurement of cosmic ray nuclei, electrons, and photons. It consists of four sub-detectors, of which the Plastic Scintillator Detector (PSD) lays on the top. The PSD, consisting of 82 bars, plays an important role in the charge (Z) measurement of cosmic rays and also acts as a veto of gamma-ray identification. In this contribution we describe a method for alignment correction of each bar of the PSD using the minimum ionization particle (MIP) spectrum. The charge resolution is improved by ∼4% after the alignment correction

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1. Introduction

DAMPE is a space-borne satellite of China that operates in solar synchronous orbit at an altitude of about 500 km for more than three years [1]. The payload of DAMPE is a high-energy cosmic ray instrument, allowing to detect particles and photons in the energy range between GeV and 100 TeV [2]. One of DAMPE sub-detectors is a Plastic Scintillator Detector (PSD) [3], composed by 82 plastic scintillator bars arranged into two layers, both layers have 39 bars with a size of $824 \times 28 \times 10$ mm^3 and two edge bars with a size of $824 \times 25 \times 10$ mm^3. Two layers are orthogonal to each other. Neighbor bars in each layer are staggered by 8 mm in order to avoid detection dead zone as shown in Fig.1. PSD plays an important role in measuring the charge of cosmic rays and also acts as a veto for gamma ray identification. The energy deposit (or most probable value of the

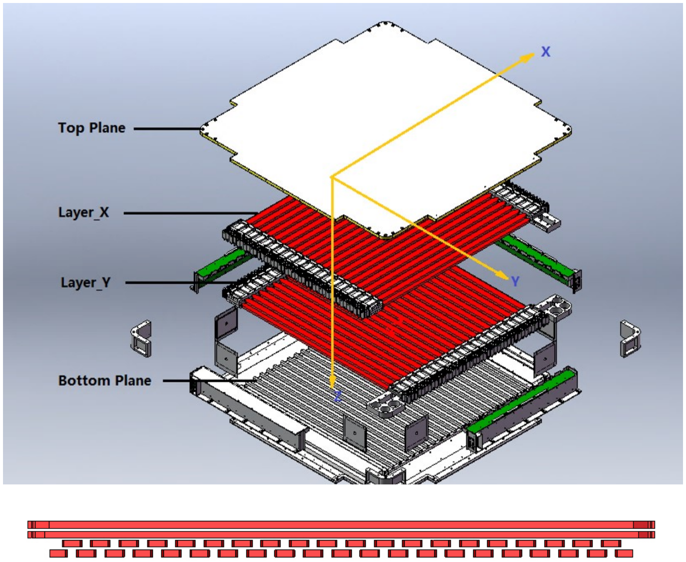

Figure 1: The arrangement of PSD bars and the side view of PSD bars. The x-y-z directions in DAMPE coordinate system are defined in the figure, PSD is located at a plane in perpendicular to z axis and the z axis points downward from PSD to NUD, PSD bars within the first layer are installed along x axis and bars within second layer are along y axis.

energy deposit) of a high-energy charged cosmic-ray particle in a PSD bar is proportional to the square of its charge and path length (hereafter PL) in the volume of a PSD bar. Therefore, in order to obtain an accurate charge measurement of a charged particle in the PSD, it is important to carry out a detector alignment of all PSD bars [4]. In this presentation, we describe the method for the alignment of all PSD bars and show the PSD geometry status in orbit.

2. Method

Due to the stability and reliability of mechanical structure of DAMPE, the shifts and rotations of PSD bars are small so that can be treated as a first-order term. The events which cross the upper and lower surfaces of a PSD bar (fully contained) are not sensitive to the shift along the bar. At the same time, the fully contained events are distorted hardly by shift and rotation (see Fig.2).

Hereafter we refer to the fully contained events and their measured energy spectrum as "middle events" and "standard spectrum", respectively. For this analysis, we select protons with minimum ionization (MIP) in orbit data. The MIP events have clear tracks with nearly zero back scattered particles, which is important for the alignment [5]. In this method, track is defined as a $3D$ line with one point (P_x, P_y, P_z) and direction (D_x, D_y, D_z).

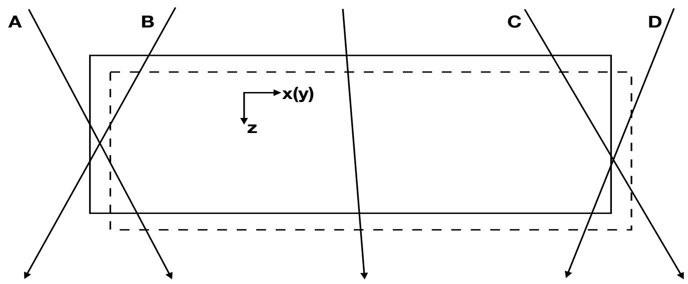

Figure 2: Schematic view of misaligned PSD bar. The *dashed* and *solid* rectangle represent the expected and real position of a PSD bar, respectively. The four event types (A, B, C and D) passing through a corner of PSD bar can be used to correct for misalignment, thanks to the dependence of PL on bar misalignment.

As mentioned above, the energy deposit of a charged particle in a PSD bar is sensitive to its PL. Position shift or rotation of a PSD bar would cause an incorrect calculation of the PL of the charged particles and thus the measured energy spectra of MIP may be distorted. Typically, 6 independent variables are needed to describe the position change of one PSD bar, which are three rotation angles ($\theta_{yz}, \theta_{xz}, \theta_{xy}$) and three shift distances ($\Delta_x, \Delta_y, \Delta_z$).

As shown in Fig.2, the events crossing a corner of a PSD bar are defined as the "corner-passing events" with four cases: A, B, C and D. In order to convert the vertical rotation into shift, each plastic bar is divided lengthwise into 11 equal virtual segments. Fig.3 shows the distribution of most probable value (MPV) of the middle events in the 902 segments (11 segments for each PSD bar, 82 bars in total). As seen from the figure, variation of the MIP spectra between the 902 segments are minor enough, meaning that the rotation angles θ_{yz} in the first layer and θ_{xz} in the second layer of PSD bars are negligible. Hence, the path length equals $\frac{\Delta Z}{\cos\theta}$ in each segment, that is, the upper surface of a PSD bar is orthogonal to z axis. In the meanwhile, shifts along the bar would not worsen the charge resolution. Finally, four effective variables remain in our alignment method, which are $\Delta_{x/y}$, Δ_z, θ_{xy}, and θ_{xz} in the first layer or θ_{yz} in the second layer, hereafter written as H, V, θ_{xy} and θ_{xz} or θ_{yz}.

According to the Bethe-Bloch formula, we use the following equation to align PSD bar.

$$E_{dep} = S \cdot PL(H, V, \theta_{xy}, \theta_{xz(yz)}), \tag{2.1}$$

where E_{dep} is the energy deposit in one bar, $PL(H,V,\theta_{xy},\theta_{xz(yz)})$ is the PL as a function of the alignment variables $(H,V,\theta_{xy},\theta_{xz(yz)})$, and S is the most probable value of energy deposit per millimeter of fully contained events in Fig.2, which is treated as the "standard value".

If a PSD bar has a shift or rotation, the real PL is:

$$PL(H,V,\theta_{xy},\theta_{yz(xz)}) = \frac{1}{\cos\theta}\cdot\left(a\frac{D_z}{D_{x(y)}}H - aV - a\Delta L_i\theta_{yz(xz)} + a\frac{D_z}{D_{x(y)}}\Delta L_i\theta_{xy} - P_z + a\frac{D_z}{D_{x(y)}}\left(X_0(Y_0) + b\frac{W}{2} - P_{x(y)}\right) - aZ_0 + \frac{T}{2}\right), \tag{2.2}$$

where ΔL_i is the offset along the bar of the i-th segment with respect to the center of a bar, ($X_0(Y_0)$, Z_0) is the ideal geometrical center point of one PSD bar, T and W are respectively the thickness and the width of one PSD bar. $a=-1$ for the cases A and D see Fig.2 and $a=1$ for the cases B and C; $b=-1$ is for the cases A and B, and $b=1$ for the cases C and D.

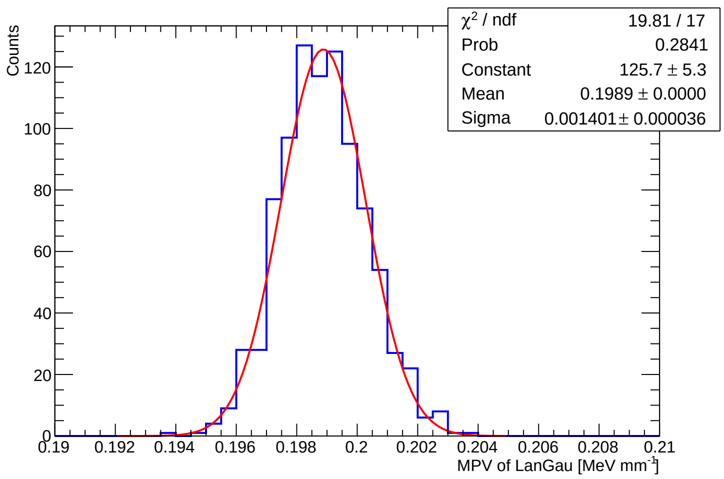

Figure 3: MPV distribution of 902 segments of all PSD bars, where the MIP events are limited to pass in the middle region of PSD bar in Fig.2. We fit the distribution with normal distribution, the *blue line* is the distribution and the *red line* is the fitting function. It is credible that these events are affected negligibly by H, V, θ_{xy} and $\theta_{xz(yz)}$.

We employ millions of MIP events to construct a series of Equations 2.1 for all PSD bars, and then use least squares to solve these equations to get H, V, θ_{xy} and $\theta_{xz(yz)}$, and make use of the alignment parameters to get new PSD geometrical center and rebuild a series of Equations 2.1, after some iterations like above we get the shift and rotation. Fig.4 shows the alignment parameters after applying our method: the horizontal shift is relatively small, [-0.27mm∼0.43mm] for the first layer and [0.25mm∼0.83mm] for the second layer, the two layers of PSD are shifted up, [-2.66mm∼-1.43mm] for the first layer and [-1.34mm∼-0.50mm] for the second layer, the rotation in xOy plane is counterclockwise and the mean of angle is about 0.0016rad, the rotation angle of first PSD layer in xOz plane is about 0.00016rad and rotation angle of second PSD layer in yOz plane is about 0.00017rad. The vertical shift is dominant among four alignment parameters. Fig.5 shows four parameters convergence of the 21^{st} bar located in the second layer.

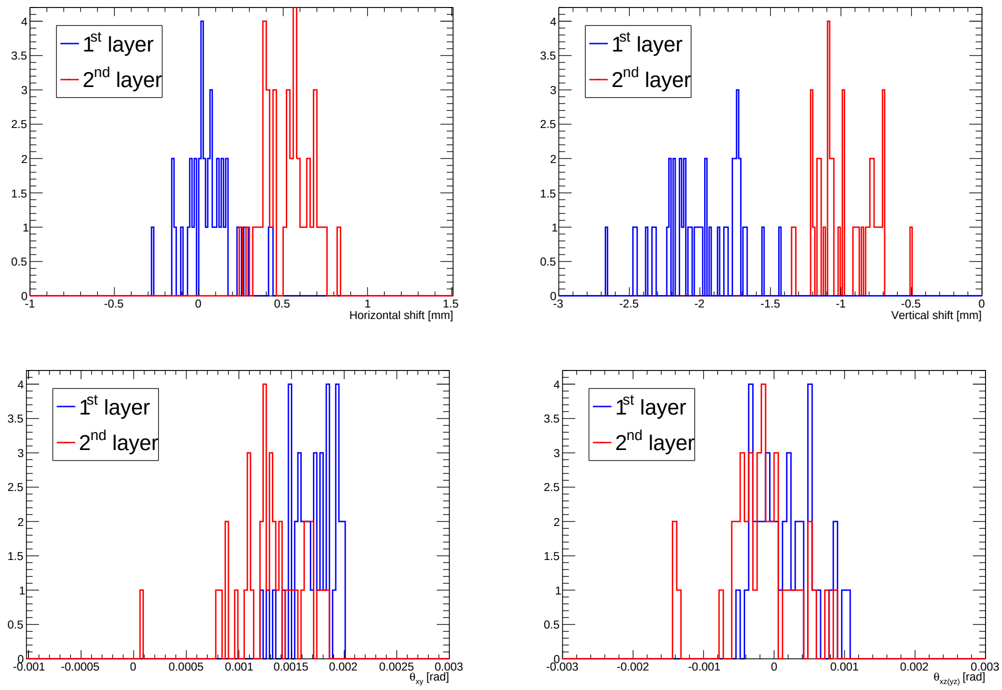

Figure 4: Distributions of the alignment parameters, the first row corresponds to H (left), V (right) and the second row corresponds to θ_{xy} (left) and $\theta_{xz(yz)}$ (right). The blue and red histograms correspond to the first and second layer respectively.

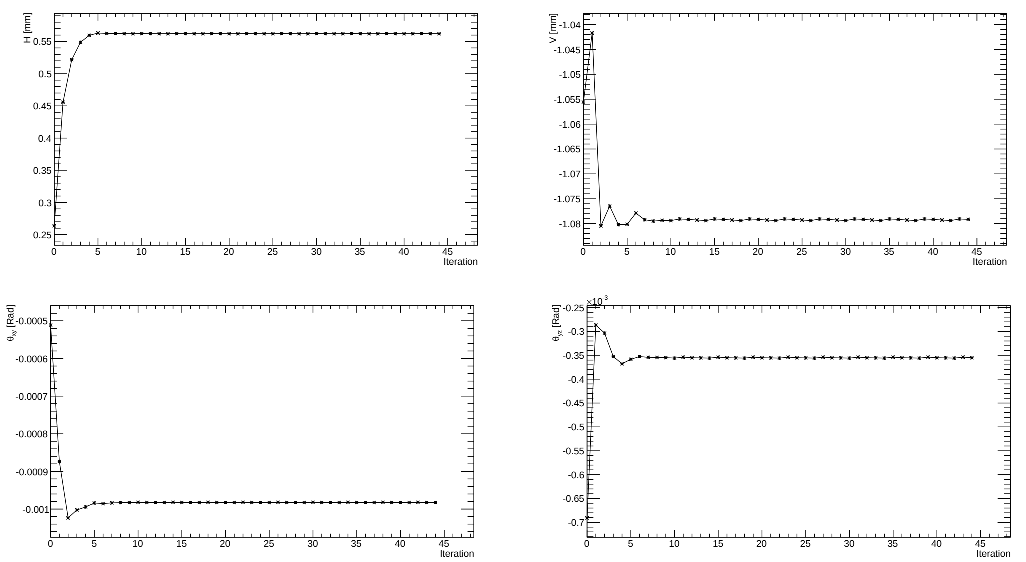

Figure 5: Convergence of alignment parameters to the 21^{st} bar in the second layer. The two plots in first row show horizontal (left) and vertical shift (right), respectively. The two plots in second row show θ_{xy} (left) and θ_{yz} (right), repectively.

Table 1: Improvement of charge resolution after applying the PSD alignment correction. The charge resolution corresponds to either a width of Landau fit (Z=1,2) or σ of Gaussian fit (Z>2).

Element	H	He	Li	Be	B	C	O	Ne	Mg	Si
before	0.0383	0.0692	0.126	0.124	0.138	0.156	0.202	0.239	0.254	0.286
after	0.0355	0.0649	0.119	0.119	0.131	0.149	0.193	0.229	0.240	0.274
Improvement	7%	6%	6%	4%	5%	5%	5%	4%	6%	4%

3. PSD status in orbit

We consider the variation of all misalignment parameters with the live-time of DAMPE in orbit, it is key factor that PSD sub-detector has a reliable temperature control system and DAMPE is still on the survey mode, which means the environment of PSD is stable. We divide all datasets into a few sub-dataset with a continuous three-month in orbit to show the variation. The variations of these 4 groups are shown in Fig.6. Almost all alignment parameters of PSD bars change very little with respect to all the alignment parameters obtained above except for the few bars located in the edge of PSD detector. The data for the bars located at the edge is limited due to the low statistics corner-passing events.

4. Conclusion

We applied the method mentioned above to the PSD sub-detector boarded on DAMPE based on the proton MIP and obtained misalignment parameters, which is helpful to improvement of charge resolution of cosmic-rays and meaningful for forward data analysis. We made a comparison on charge with the PSD before alignment and after ones as shown in Fig.7. Alignment correction had been applied to charge reconstruction [6], we found the improvement on charge resolution is by at least 4% as shown in Table.1. The stability of the PSD alignment is verified by comparing MIP data from different periods on orbit. Minor variation of alignment parameters is observed, consistent with a small seasonal temperature variation of the PSD (within 1 degree Celsius). However this variation has negligible impact on the PSD charge reconstruction. We believe that our methodology can be successfully applied for the alignment of other large-scale detector units.

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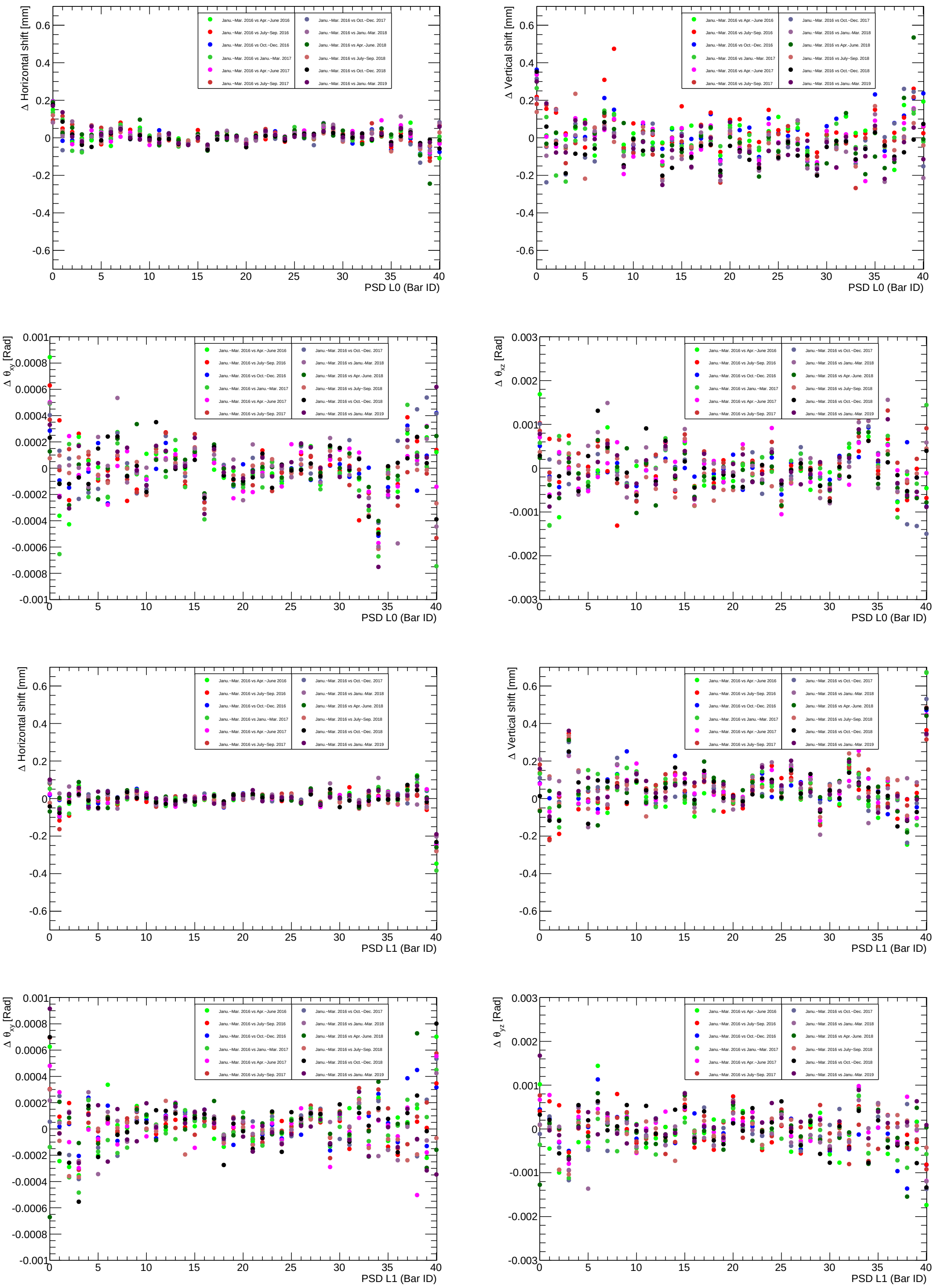

Figure 6: Variations of misalignment parameters in different time from 20160101 to 20190331. Each filled circle represents one PSD bar, the ones with different color shows the variation compared with alignment parameters obtained from Jan. 2016 to Mar. 2016. The first row from left to right corresponds to variations of H and V of first PSD layer, the second row from left to right corresponds to variations of θ_{xy} and θ_{xz} of first PSD layer, the last two rows correspond to variations of parameters of second PSD layer.

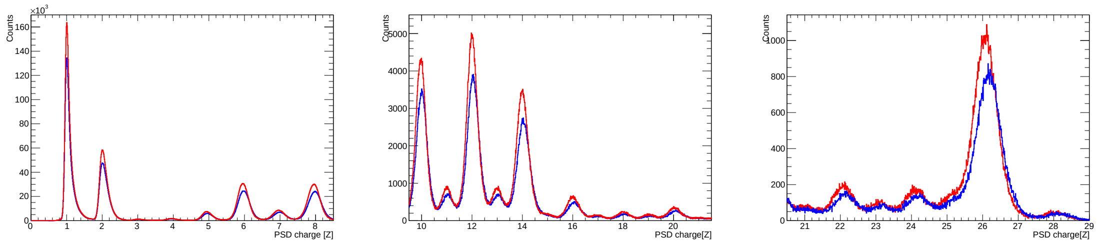

Figure 7: The Comparison of PSD charge spectrum with or without the correction: the *red line* is PSD charge with alignment correction, the *blue one* shows the charge without alignment correction. One can see the significant improvement of charge resolution, which is particularly important for the physics analysis of cosmic rays

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