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Magnetic shielding for DAMPE electromagnetic calorimeter PMTs*

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Abstract: The magnetic characteristics of R5610A-01 photomultiplier tubes are studied in this paper. The experimental data shows that the gain of R5610A-01 loses about 53% when the magnetic field is 3 Gs along its $+X$ axis. A cylinder of one-layer permalloy strip is able to reduce the effect of a 3 Gs magnetic field on the PMT gain to less than 1%.

Key words: photomultiplier tube, magnetic shield, characteristics

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1 Introduction

DAMPE, DArk Matter Particle Explorer, is a detector focusing on high energy electron and gamma ray detection. The program is building a 60 cm×60 cm×60 cm bismuth germanate (BGO) calorimeter which will be loaded on a satellite to study the properties of high energy particles in space. This BGO calorimeter will use 616 Hamamatsu R5610A-01 photomultiplier tubes (PMT). Because of the satellite's inner magnetic field and the earth's magnetic field, the maximum magnitude of the magnetic field that the BGO calorimeter will sustain is 2.1 Gs. Since the PMT is very sensitive to magnetism [1, 2], it is necessary for us to shield the PMT from the magnetic field. Simulation results from Geant4 show that if we want the energy resolution of the BGO calorimeter for e/γ to reach 1.5% at 800 GeV [3], then the effect on PMT signal variation of magnetic field must be less than ±1%. Very strict mass limitations on the satellite's load require that the material for the magnetic shield be as light as possible. In this work, we test the effects of magnetic field on the Hamamatsu R5610A-01 PMT. In the following, we first present the experimental setup in Section 2, followed by results and discussion in Section 3, then conclusions in Section 4.

2 Experimental setup

2.1 Building a variable magnetic field

To produce a stable and uniform magnetic field for the test of the PMT's magnetic characteristics, a Helmholtz coil was designed and assembled. The formula for magnetic induction at the midpoint between two coils was used [4]:

$$B=\left(\frac{4}{5}\right)^{3/2}\frac{\mu_0 nI}{R},$$

where μ_0 is the permeability of free space, n is the number of turns in each coil, I is the current flowing through the coils and R is the radius of the coils and also the distance between the two coils.

To produce a magnetic field of more than 2.1 Gs, the parameters of the Helmholtz coil were designed as follows (Table 1).

Table 1. Design parameters of the Helmholtz coil.

parameter	value
diameter of the coils	300 mm
number of turns per coil	18
current range flowing through the coils	0–3.2 A
magnetic field range	0–3.77 G

The diameter of the coils was set to 300 mm. This can ensure the field's uniform zone (about 100 mm×100 mm×100 mm) is large enough to place the R5610A-01 PMT (Φ18.5 mm×30 mm). The material of the coil frames is nylon, to avoid disturbing the magnetic field.

As shown in Fig. 1, the Z axis of R5610A-01 is located in the middle plane of the coils and parallel to the tube axis. The R5610A-01 can rotate around its Z axis to find the X and Y axis relative to the field's lines. A magnetometer with an accuracy of 0.001 Gs was used to measure the magnetic field of the coils. The power sup-

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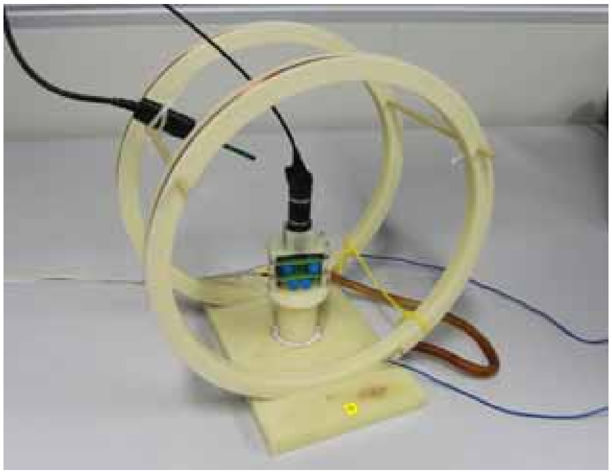

Fig. 1. The Helmholtz Coil. LED light was transmitted to the PMT by optical fiber. The magnetometer sensor was fixed on the coil to monitor the magnetic field at the midpoint of the coils.

ply that drove the Helmholtz coil has a current stability of 0.2%.

2.2 Data acquisition system

Figure 2 shows the block diagram of the data acquisition system. The blue LED was located far from the effects of the Helmholtz coil field. An optical fiber guided light pulses to the entrance window of the R5610A, which sat on a rotating table between the coils. A pulse generator with voltage stability better than 1% drove the LED and synchronously sent a trigger pulse to the gate generator. A CAEN N1470 with voltage stability of ±0.02% in one week was used to supply the R5610A. The charge signal of dynode 8 responding to the LED's light pulse was sent to the FEE (Front-End Electronics), by which the charge signal was amplified and the gate pulse timed with the amplified voltage pulse. The digitized counts proportional to the charge were then output from an ADC chip and the data recorded by the computer. A Gaussian was fit to the spectra and the peak channel (ADC channel) was obtained.

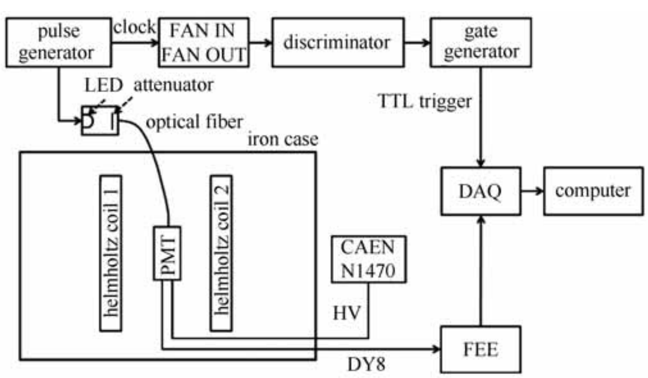

Fig. 2. Block diagram of the data acquisition system.

2.3 Checking the stability of the whole system

After building the whole test system, its stability was checked. We adjusted the Helmholtz coil field to cancel out the earth's magnetic field and then traced the PMT signal variation at B=0 Gs for 24 hours with a constant light pulse driving. The results show that the period from 0:00 to 9:00am is the quietest time over the 24 hours. Fig. 3 shows the results acquired during that quietest period. The ADC channels show a normal distribution with a mean value of 4037.57 and σ of 4.25. The stability is ∼0.1% in 9 hours.

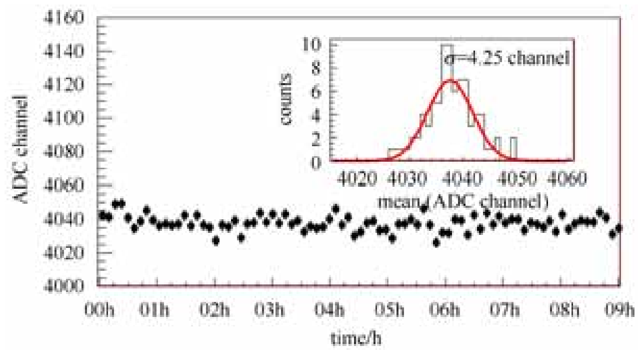

Fig. 3. Stability of the whole system from 0:00am to 9:00am with $B = 0$ Gs.

3 Results and discussion

3.1 PMT sensitivity in the X-Y plane

In the photoelectron multiplication process of the PMT, a special configuration of the electric field is designed using a series of dynodes to accelerate, multiply and focus the electrons. The external magnetic field will destroy the electron paths and cause the electrons to escape collection and multiplication by the next dynode. The first few dynodes are the most sensitive to the magnetic field because the electron kinetic energies are lower there and those electrons contribute with more weight to the final output. Due to the orientations of the first few dynodes, when the external magnetic field lines are perpendicular to the electric field lines between dynodes, the path destruction and the gain suppression are the greatest. The PMT orientation which is most sensitive to the magnetic field will be defined as the X axis. To find this orientation, a 1 Gs field of the Helmholtz coil was set while rotating the R5610A around the Z axis (see Fig. 1). The spectra of R5610A responding to a constant LED pulse with various rotating angles was taken. Fig. 4 shows that the angle orientation of 270°, where the gain suppression is the greatest, is the X axis, and the angle orientation of 180°, where the gain suppression is the least, is the Y axis.

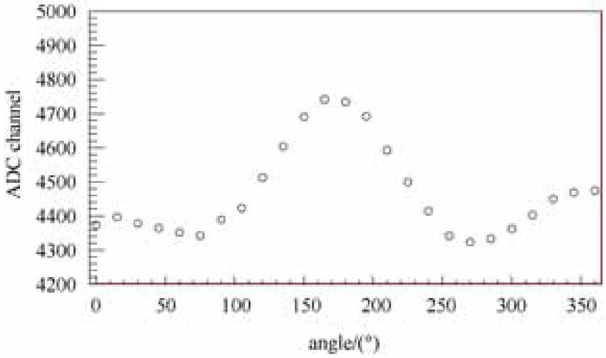

Fig. 4. Signal variation of the PMT with the angle of the magnetic field in the X-Y plane when the magnetic magnitude is 1 Gs.

3.2 Variation of R5610A gain with magnetic field magnitude

Rotating the R5610A's X axis parallel to the field lines of the Helmholtz coil, with constant LED light pulses and HV settings, the spectra of the charge output from dynode 8 was taken under field magnitudes of 0, 1, 2 and 3 Gs respectively. The data represented by full squares in Fig. 5 show the peak channels vary with the magnetic field along the $+X$ (top) and $-X$ (bottom) axes. Rotating the $\pm Y$ axis and $\pm Z$ axis of the R5610A along the direction of magnetic field, and repeating the same cycle as the $\pm X$ case, resulted in the data represented by full triangles and full circles in Fig. 5, which show how the peak channels vary with magnetic field along $+Y$ and $+Z$ (top), $-Y$ and $-Z$ (bottom) respectively.

As shown in Fig. 5, a 3 Gs field in the $\pm X$ direction of the R5610A makes its gain lose ~53% ($+X$) and 43% ($-X$) compared to the 0 Gs case. For the Y direction, the gain is much less sensitive to the magnetic field; gain loss is only 4% ($\pm Y$). Up to a maximum 3 Gs in the Z-direction there is no visible effect on the gain of the R5610A.

3.3 Magnetic shield on PMT R5610A-01

From electromagnetic field theory [5], a film of thickness t and magnetic permeability $\mu_{\rm I}$ wrapped as a closed cylinder of a radius r, can reduce a magnetic field perpendicular to the axis of the cylinder from $H_{\rm out}$ to $H_{\rm in}$:

$$\frac{H_{\rm out}}{H_{\rm in}}=\left(\frac{3t\mu_{\rm I}}{4r}\right)^n,$$

n being the number of individual layers of the film used to form the shield cylinder.

Permalloy strips (Fe-Ni-alloy of $\mu_{\rm I}$= 8000) of 27 μm thickness and 25 mm width were used to form a shield cylinder with inner diameter Φ19 mm, matching the R5610A's diameter. At first, we put a cylinder of one-layer permalloy in the midpoint between the two coils with the cylinder's axis perpendicular to the direction of the 3 Gs field. The magnitude of the field in the center of the cylinder was measured to be 0.16 Gs, ~1/18 of the coils' field.

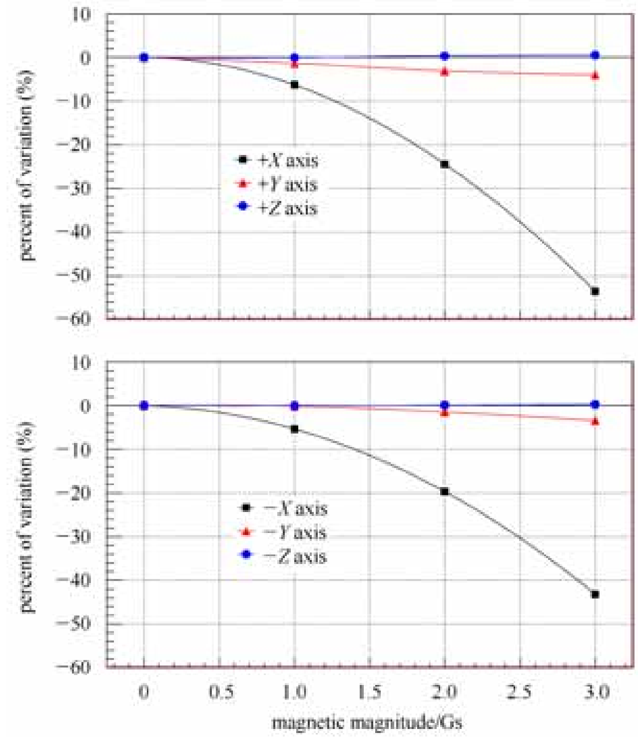

Fig. 5. PMT signal variation with the magnitude of magnetic field in $\pm X$, $\pm Y$ and $\pm Z$ directions.

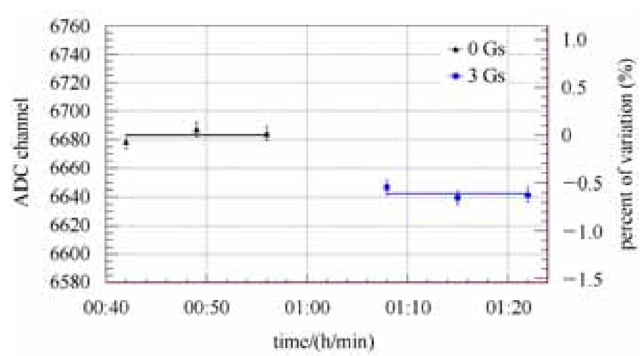

Fig. 6. The shield result of a cylinder of one-layer permalloy strip.

The cylinder of one-layer permalloy was then wrapped around the R5610A with its edge level to the R5610A's entrance window. The PMT and the cylinder were located in the position where the PMT's X orientation was along the axis of Helmholtz coils. Running the data taking program with B=0 and B=3 Gs respectively during the quietest period of the day, 3 sets of data were acquired for each situation. After fitting the spectra, 3 peak channels (ADC channel) were obtained and averaged. The results in Fig. 6 show that a cylinder of one-layer permalloy strip of 27 μm thickness and 25 mm width is able to shield the R5610A from a field of 3 Gs with a gain loss less than 1%. This has met the requirement of the energy resolution of the calorimeter.

4 Conclusion

The photomultiplier tube is very sensitive to external magnetic fields, because they seriously disturb the photo-electron paths defined by the dynode structure. Data shows that the gain of the R5610A loses 53% (+X orientation) and 4% (+Y orientation) when the magnetic magnitude increases from 0 to 3 Gs. Along the Z orientation there is no visible change in the gain. A cylinder of one-layer permalloy is able to keep the gain loss of the R5610A to less than 1% (∼0.6%) under magnetic fields of 3 Gs.

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