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Light-weight flexible magnetic shields for large-aperture photomultiplier tubes

P. DeVore [a,b], D. Escontrias [b], T. Koblesky [c], C.J. Lin [b], D.W. Liu [b], K.B. Luk [a,b,*], J. Ngan [b,d], J.C. Peng [c], C. Polly [c], J. Roloff [c], H. Steiner [a,b], S. Wang [a,b], J. Wong [b,d], M. Yeh [e]

[a] Department of Physics, University of California, Berkeley, CA 94720, USA
[b] Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[c] Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
[d] Department of Physics, Chinese University of Hong Kong, Hong Kong, China
[e] Chemistry Department, Brookhaven National Laboratory, Upton, NY 11973, USA

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ABSTRACT

Thin flexible sheets of high-permeability FINEMET® foils encased in thin plastic layers have been used to shield various types of 20-cm-diameter photomultiplier tubes from ambient magnetic fields. In the presence of the Earth's magnetic field this type of shielding is shown to increase the collection efficiency of photoelectrons and can improve the uniformity of response of these photomultiplier tubes.

1. Introduction

It is well known that the performance of most photomultiplier tubes (PMTs) is susceptible to even small local magnetic field such as that of the Earth, which is typically in the range of 0.4–0.5 G [1]. The impact of this kind of weak magnetic field can be reduced by shielding the PMT, especially the region near the photocathode, with high-permeability materials such as mu-metal.

We describe here a new type of magnetic shield that has been developed at the Lawrence Berkeley National Laboratory for use in the Daya Bay Reactor Neutrino Oscillation Experiment [2]. It utilizes FINEMET, a novel thin flexible high-permeability material, to form a truncated cone around a large-aperture PMT behind the photocathode. In the following sections we describe the detailed characteristics of this shield, and present experimental results showing its impact on the performance of some selected PMTs. In particular we will show that it reduces variations in the PMT response caused by changes in the relative orientation of the PMT and magnetic field, and that it significantly improves the electron collection efficiency of the PMT. These improvements have a direct impact on the physics objectives of an experiment in that they result in a greater uniformity of response of the detector, and thereby yield a more reliable measurement of the energy of an event.

2. Effect of magnetic field on PMT

We have investigated the effect of the magnetic field on the gain and charge collection of some large-aperture PMTs. These results are of particular relevance to experiments where the events of interest produce at most a few photoelectrons (PEs) in a given PMT. The magnetic field also affects multi-photoelectron events, but in this case it is not possible to separate the effects caused by gain variation from those attributable to collection efficiency. In this study we used Electron Tubes 9354KB [3], Hamamatsu R5912 [4], and Photonis XP1806 [5] 20-cm PMTs.

2.1. Effect of magnetic field on collected amount of charge

We determined the effect of the local magnetic field on the response of a PMT by positioning the PMT with its polar axis perpendicular to the field, as shown in Fig. 1(a). The PMT was mounted on a holder that could be rotated about the polar axis from outside of the dark box containing the PMT. Light from a pulsing blue LED illuminated the entire photocathode, and its intensity could be controlled as needed in the study. The charge associated with the PMT signal was measured with an analog-to-digital converter (ADC) as a function of the angle between the local magnetic field and a reference on the PMT, denoted by ϕ. In this study, the polarized key on the socket of the PMT, shown in Fig. 1 (b), was chosen as the reference direction. When this reference direction was parallel (normal) to the local field, ϕ was 0° (90°).

* Corresponding author.
E-mail address: k_luk@berkeley.edu (K.B. Luk).

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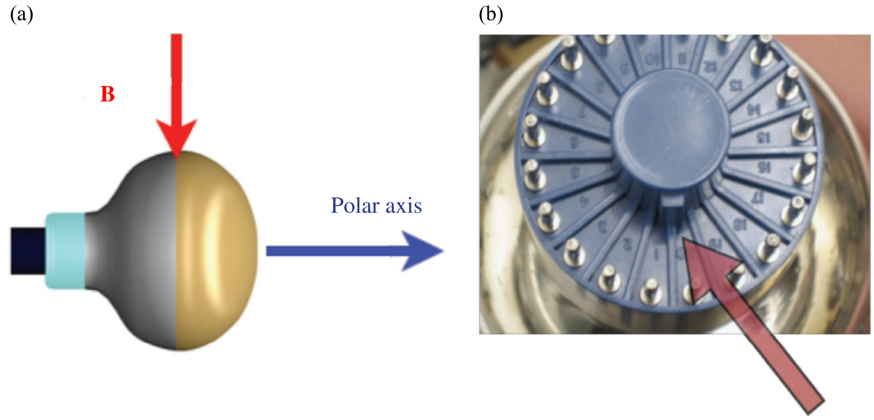

Fig. 1. (a) Orientation of the PMT with respect to the local magnetic field for evaluating response. (b) PMT reference direction: the polarized key between pin 1 and pin 20 indicated by the arrow is used as the PMT reference direction.

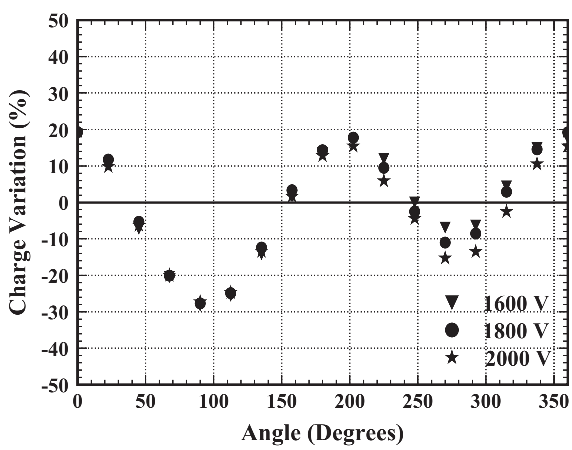

Fig. 2. Effect of magnetic field on collecting charge for an unshielded Electron Tube 9354KB PMT as a function of the angle between the PMT reference direction and the magnetic field.

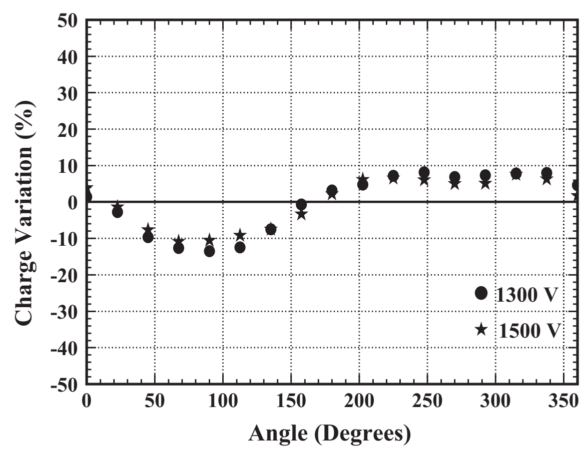

Fig. 3. Effect of magnetic field on collecting charge for an unshielded Hamamatsu R5912 PMT as a function of the angle between the PMT reference direction and the magnetic field.

The ϕ-dependence of the charge variation at some operating high voltages for the Electron Tubes 9354KB, Hamamatsu R5912, and Photonis XP1806 PMTs is shown in Figs. 2–4 respectively. The charge variation, ΔQ, is defined as

$$\Delta Q(\phi) = \left(\frac{Q(\phi) - \overline{Q}}{\overline{Q}} \right) \times 100\% \tag{1}$$

where $Q(\phi)$ is the amount of charge collected at angle ϕ, and $\overline{Q}$ is the average amount of collected charge given by

$$\overline{Q} = \frac{1}{N} \sum_{i=1}^{N} Q(\phi_i) \tag{2}$$

with N being the number of measurements done at various ϕ values.

For each type of PMT the result is quite insensitive to the applied voltage. The difference in the observed behaviour between the three PMT models is a consequence of the different designs of the dynode structure and focussing scheme. Fig. 5 shows the opening to the first dynode for these three kinds of PMTs. Electron Tubes 9354KB has the smallest opening (most affected) whereas Photonis XP1806 has the largest opening (least affected).

2.2. Effect of magnetic field on single-photoelectron (SPE) spectrum

A revealing way to study the influence of the magnetic field on the detected charge is to use single-photoelectron events. By making this measurement without a magnetic shield we can directly determine how the shield affects both the gain and the collection efficiency of the PMT. The SPE spectrum can be obtained by reducing the light intensity on the photocathode until only about 10% of the triggers produce a signal. From Poisson statistics about 95% of the observed pulses are produced by SPEs. The spectrum of the charge collected at the anode under this condition is shown in Fig. 6. Since the charge of a single electron is known a

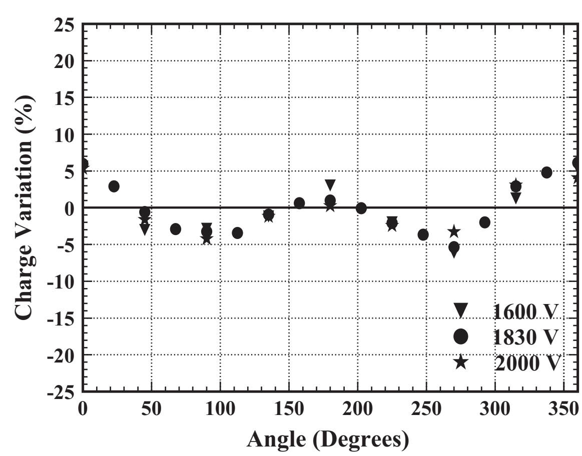

Fig. 4. Effect of magnetic field on collecting charge for an unshielded Photonis XP1806 PMT as a function of the angle between the PMT reference direction and the magnetic field.