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Study on Fine-mesh PMT's for Detection of Aerogel Čerenkov Light

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Abstract

Most recent fine-mesh photomultipliers (FM-PMT's), with 19 dynode stages, have been tested for application to a threshold aerogel Čerenkov counter. Two properties, the gain and the pulse height resolution, have been particularly studied in a magnetic field of up to 1.5 T. The obtained results show that a FM-PMT is a suitable device for detection of aerogel Čerenkov light.

1 Introduction

In experimental high energy physics in recent years, there is an increased demand for photon detectors that can operate in a strong magnetic field. A fine-mesh photomultiplier tube (FM-PMT) is one of the most promising devices due to its large effective area and high gain. These properties are of particular importance in the application to Čerenkov counters, where expected light yields are small compared to other applications such as to calorimeters and scintillation counters.

In the BELLE experiment at the KEK B-factory, FM-PMT's will be used for a threshold aerogel Čerenkov counter (ACC) system, which functions to separate charged pions and kaons in the momentum region from 0.8 to 3.5 GeV/c [1, 2]. The ACC system consists of 1188 radiator boxes which contain silica aerogels with low refractive indices ranging from 1.010 to 1.030 [3, 4]. The whole system is located inside a solenoid magnet with a field strength of 1.5 T. Each radiator box is equipped with either one or two FM-PMT's with diameters of 2", 2.5" or 3". The expected light yield varies from about 10 to 20 photoelectrons for charged pions in the above momentum region of interest.

In our previous work [5], feasibility of FM-PMT's for single-photon counting was studied using experimental data and a Monte Carlo simulation. It was suggested that single-photon efficiency can be improved by increasing the number of fine-mesh dynodes. In the present work, effects of a magnetic field on PMT performance, in particular, the gain and the pulse height resolution, have been extensively studied for most recent FM-PMT's, with 19 fine-mesh dynode stages.

2 Fine-mesh PMT

The FM-PMT's tested in this work were R5924(2"), R6505(2.5"), R5542 and R5543 (3") from Hamamatsu Photonics [6]. All samples were equipped with a bialkali photocathode and 19 fine-mesh dynode stages. The diameter of effective photocathode area, equal to the diameter of dynodes, was 39 mm, 51 mm and 64 mm for 2", 2.5" and 3" tubes, respectively. The average quantum efficiency of obtained samples, 80 pieces in total, was estimated to be 25% at the wave length of 400 nm. In the measurements described below, voltage dividers provided by the manufacturer, which gave voltage drop between the photocathode and the first dynode equal to twice as that between the other dynodes, were used.

In order to improve the gain in a magnetic field, several modifications of fine-mesh dynodes were tried. The FM-PMT samples tested in this work were categorized into three types, type-A, B and C. The type-A samples were conventional ones, having dynodes with a typical mesh width of about $6\mu m$ and a mesh spacing of about $17\mu m$. The type-B and type-C samples were improved ones, which were more recent products. They were produced using dynodes with a finer mesh spacing, compared to type-A, aiming at improved magnetic field immunity. The type-C samples were further optimized aiming at improved absolute gains.

3 Test setup

Figure 1 shows the setup of the measurements. Four FM-PMT's were mounted on a box equipped with five light emitting diodes (LED's), and tested simultaneously. The LED had a peak wave length of 470 nm with a spread of 70 nm in FWHM. The five LED's were flushed at the same timing by a 50 ns wide pulse generated by a pulse generator (IWATSU PG-230). The light emitted from each LED was reflected diffusively by white reflector ("Goretex" [7]) in order to illuminate the photocathode uniformly. The photocathode was masked to the diameter of the dynodes.

A dipole magnet at KEK ("Ushiwaka"), with a gap of 30 cm and a pole length of

70 cm, was used to provide a magnetic field of up to 1.5 T. The box could be rotated from outside the magnet, and the gains and the pulse height resolutions were compared at four different angles between the field direction and the PMT axis (θ) from 0° to 45°.

Signals from FM-PMT's were digitized by a CAMAC ADC (LeCroy 2249A), and data were recorded with a workstation (Fujitsu S4/IX). A 100 ns gate was generated for the ADC by the pulse generator used to flush the LED's. When signals were small due to a strong magnetic field over 1 T, a fast linear amplifier (Hamamatsu C5594), with a voltage gain of 63 and a band width of 50 kHz $\sim$ 1.5 GHz, was used. For some measurements, signals were fed to the ADC through variable attenuators for adjusting the pulse height to a comfortable ADC range.

4 Improvement of gains for recent FM-PMT's

The gain performance has been tested for 3, 8 and 11 samples of type-A, B and C, respectively. According to data sheets provided by the manufacturer, in absence of a magnetic field, the average gain with a cathode to anode voltage (V) of 2000 V is 3.1×10^7, 1.9×10^7 and 7.9×10^7 for type-A, B and C, respectively.

Figure 2 shows the gain (G) relative to $B = 0$ case (G_0) as a function of the field strength (B). The voltage V applied to each PMT is fixed at about 2000 V. For each measurement, a relative gain is calculated from the mean of a recorded ADC spectrum, taking account of known corrections such as due to the amplifier and the variable attenuator. The solid lines show the result for type-B, averaged over eight samples, at four angles of the field direction ($\theta = 0°, 15°, 30°$ and $45°$). The gain is lowest when the field is parallel to the PMT-axis ($\theta = 0°$) and the highest gain is obtained at $\theta = 45°$ in the measured range of the angle.

For comparison, the dashed lines in Figure 2 shows the result for type-A samples, average of three samples, at angles of 0° and 30°. At $B = 1.5\,\mathrm{T}$, the ratios G/G_0 for 0° and 30° are 5.3×10^{-3} and 3.6×10^{-2}, respectively, for type-B, while they are 3.3×10^{-4} and 3.0×10^{-3}, respectively, for type-A. Therefore, the gain reduction for type-B is an order of magnitude smaller than type-A.

In Table 1, average gains measured for the three types at angles of 0° and 30° are summarized. The absolute gain in a magnetic field G is estimated from the measured relative gain G/G_0 and the gain measured at $B = 0$ by the manufacturer. As for the type-C samples, it appears that the extremely high gains at $B = 0$ are obtained by sacrifice of the magnetic field immunity. Improvement of the gain reduction, compared to type-A, is only by a factor of 3. Nevertheless, the improved FM-PMT's, both type-B and type-C, have absolute gains improved by a factor of more than 6 compared to the conventional type-A samples.

For type-B and type-C samples, dependence of the gain on the voltage has been tested in the range from 1800 to 2800 V. The dependence can be well parametrized in the form of $G \propto V^{\alpha}$. Difference between the two types is not significant. On the average of tested samples, the parameter α at $B = 1.5\,\mathrm{T}$ is 7.0 and 8.0 for 0° and 30°, respectively, whereas that for $B = 0$ is 8.2. At 2500 V, for example, the average gain at $B = 1.5\,\mathrm{T}$ reaches $4 \sim 6 \times 10^5$ and 5×10^6 for 0° and 30°, respectively, as shown in Table 1.

5 Study on pulse height resolution

Effects of a magnetic field on the pulse height resolution have been evaluated by tracing the change of a quantity N_{eff}, which is defined as $N_{eff} = (\mu/\sigma)^2$, by using the mean (μ) and sigma (σ) of the recorded ADC spectrum. The quantity N_{eff} represents the effective photostatistics for the spectrum, which is a convolution of a single-photoelectron (p.e.) response of the device and the Poisson statistics with N_{pe}, the average number of photoelectrons emitted from the photocathode. For FM-PMT's, the ratio N_{pe}/N_{eff}, referred as "excess noise factor", is about 2 at $B = 0$ [8]. The relatively large excess noise factor is because of the fact that a single-p.e. spectrum for a FM-PMT does not have a peak, as discussed in [5]. In the present work, reduction of N_{eff} in a magnetic field has been measured for 2", 2.5" and 3" FM-PMT's in the categories of type-B and type-C. No significant difference between the two types has been seen for this property. For each measurement, N_{eff} at $B = 0$ (N^0_{eff}) is about 20.

In Figure 3, the change of N_{eff} normalized by N^0_{eff} is plotted as a function of magnetic field strength for typical 2" and 3" samples at four angles of 0°, 15°, 30° and 45°. The data were taken with a fixed voltage in the range from 2000 V to 2200 V. Table 2 shows the ratio N_{eff}/N^0_{eff} at $B = 1.5\,\mathrm{T}$ for 0° and 30°, averaged over tested samples for each size. The number of tested samples for each size and angle is shown in parenthesis. As the field B increases, the resolution deteriorates and the quantity N_{eff} decreases. At the voltage in this range, the following tendencies are found. First, the decrease in N_{eff} is larger when the field is at a large angle such as 30° than the case of $\theta = 0°$. Second, the decrease in N_{eff} at a large angle is more significant for the smaller FM-PMT's (2" or 2.5") than the larger one (3").

These tendencies can be understood qualitatively by the following simple geometrical consideration. In a high enough magnetic field, the electron avalanche follows the field lines. In case that the field direction is at a large angle, the center of gravity of the electrons moves away from the anode center when they reach the anode. This gives significant loss in the charge collection on the anode, resulting in more statistical fluctuation in the observed pulse height. The more significant decrease in N_{eff} for the smaller FM-PMT is thought due to a smaller aspect ratio, the ratio of the dynode diameter to the distance between the photocathode and the anode (about 20 mm not depending on the PMT size).

However, it is noticed that, in a magnetic field, the resolution improves, namely the quantity N_{eff} increases, by applying higher voltage, while no significant change is found in absence of the field. Table 2 shows the ratio N_{eff}/N^0_{eff} at $B = 1.5\,\mathrm{T}$ with the applied voltage in a higher range, $2600 \sim 2800\,\mathrm{V}$. Although the decrease in N_{eff} is still larger for the smaller PMT, the difference between 0° and 30° is not so significant. The voltage dependence of N_{eff} in a magnetic field cannot be explained by the above simple geometrical consideration. More studies on electron avalanche processes in a magnetic field is necessary to understand the phenomena.

6 Application to Čerenkov counters

Based on the above presented performance in magnetic fields, application of FM-PMT's to Čerenkov counters is discussed in this section. We assume that the angle θ is close to 0° or 30°, as in the BELLE ACC system [1, 2].

With recent improved FM-PMT's, either type-B or type-C, the gain reachable at 2500 V is as high as $4 \sim 6 \times 10^5$ even at $\theta = 0°$, the lowest gain arrangement. This is a great advantage of FM-PMT's for detecting Čerenkov photons with a good signal-to-noise (S/N) ratio. For the BELLE ACC system, the expected electronic noise level is 10^4 or less in electron equivalent charge. Therefore, even for signals at a single p.e. level, the S/N ratio is expected to be higher than 10.

In application to threshold Čerenkov counters, one must be aware that the separation between two particle species is determined by the quantity N_{eff} rather than N_{pe}. The large excess noise factor of about 2 even without a magnetic field, as mentioned already, dominates the total loss of the effective photostatistics from the original Poisson statistics with N_{pe}. Although the loss in the quantity N_{eff} due to a magnetic field is as high as 30% ($N_{eff}/N^0_{eff} \sim 0.7$), it can be minimized by optimizing the angle θ, the choice of the PMT diameter and the applied voltage. The detector must be designed so that the photoelectron yield N_{pe} is high enough to overcome the total loss. In the case of the BELLE ACC system, the expected light yield (N_{pe}) for light velocity particles is approximately 20, giving N_{eff} of about 7 at $B = 1.5\,\mathrm{T}$. More than 3σ π/K separation is then expected in the momentum region of interest from 0.8 to 3.5 GeV/c [2].

7 Summary

In the present work, performance of most recent FM-PMT's with 19 fine-mesh dynode stages, in particular the gain and the pulse height resolution, has been studied. The obtained gain in a magnetic field of 1.5 T, improved by a factor of about 6, ensures a good signal to noise ratio even for signals at a single-p.e. level. The loss of effective photostatistics in a magnetic field due to deterioration of the pulse height resolution can be minimized by optimizing the detector configuration, choice of the PMT size and the applied voltage value. We conclude that a FM-PMT is a suitable device for threshold aerogel Čerenkov counters in strong magnetic field environment.

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Table 1: Results of gain measurements for type-A, B and C samples.

Type	G_0	G/G_0		G		G	
(#sample)	2000 V	2000 V		2000 V		2500 V	
	$B = 0$	$B = 1.5\,\mathrm{T}$		$B = 1.5\,\mathrm{T}$		$B = 1.5\,\mathrm{T}$	
		$\theta = 0°$	$\theta = 30°$	$\theta = 0°$	$\theta = 30°$	$\theta = 0°$	$\theta = 30°$
A (3)	3.1×10^7	3.3×10^{-4}	3.0×10^{-3}	1.0×10^4	9.2×10^4	—	—
B (8)	1.9×10^7	5.3×10^{-3}	3.6×10^{-2}	9.3×10^4	6.3×10^5	6.5×10^5	5.4×10^6
C (11)	7.9×10^7	9.1×10^{-4}	8.6×10^{-3}	6.8×10^4	6.8×10^5	4.0×10^5	5.5×10^6

Table 2: Measured ratio N_{eff}/N^0_{eff} at $B = 1.5\,\mathrm{T}$. The number of tested samples for each condition is shown in parenthesis.

PMT diam.	$2000 \sim 2200\,\mathrm{V}$		$2600 \sim 2800\,\mathrm{V}$	
	$\theta = 0°$	$\theta = 30°$	$\theta = 0°$	$\theta = 30°$
2"	0.74 (7)	0.64 (10)	0.75 (10)	0.73 (10)
2.5"	0.80 (5)	0.73 (5)	0.85 (8)	0.85 (8)
3"	0.79 (2)	0.77 (4)	0.87 (6)	0.99 (7)

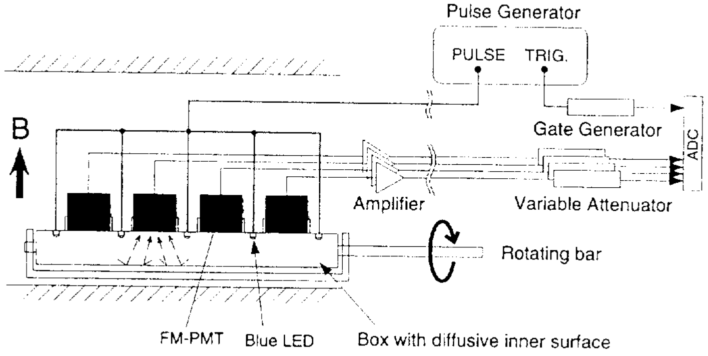

Figure 1: Setup of the measurement in a magnetic field.

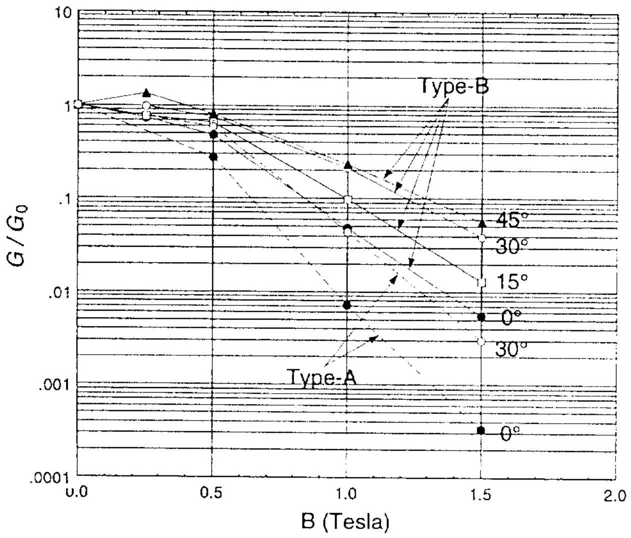

Figure 2: Change of gains (G/G_0) as a function of magnetic field strength. The solid lines show the results for type-B (average of 8 samples) at 0°, 15°, 30° and 45°. The dashed lines show the results for type-A (average of 3 samples) at 0° and 30°.

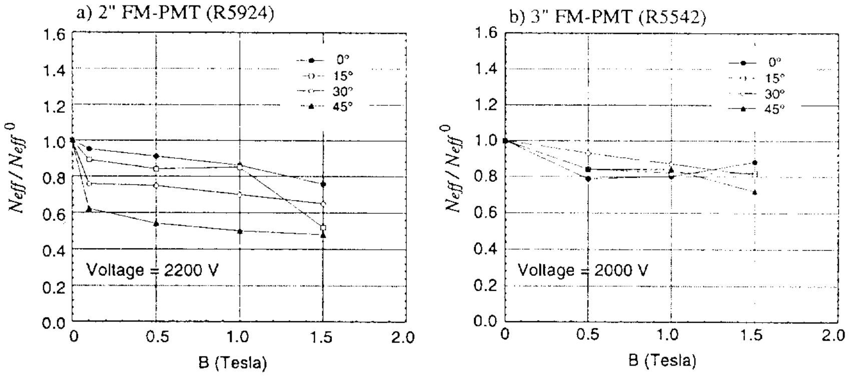

Figure 3: Change of N_{eff} as a function of magnetic field strength for typical a) 2" and b) 3" samples.