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Tests of Photon-Detection Devices in Strong Magnetic Fields

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Abstract

Three types of photon-detection devices (FMPMT, HPMT, and VAPD) were tested in strong magnetic fields. The maximum strength of the magnetic field applied in the test was 2.5 Tesla for the FMPMT and HPMT, and 1.0 Tesla for the VAPD. We measured the dependence of the gain on the magnetic-field strength as well as on the angle between the device axis and the magnetic field.

1 Introduction

In future collider experiments it will be essential to have a hermetic detector and good calorimetry energy resolution. In order to fulfill both the requirements, it is preferred to locate the calorimeter inside a solenoidal magnet. However, since hadronic calorimeters are usually made with a sampling configuration, their output photons are not sufficient to be read out with PIN silicon photodiodes. It is thus necessary to develop photon-detection devices with high sensitivity, which are operational in strong magnetic fields.

In this report we present test results of three different photon-detection devices in strong magnetic fields: a fine-mesh photomultiplier (FMPMT), a hybrid photomultiplier (HPMT), and a vacuum avalanche photodiode (VAPD).

It is well known that FMPMT's are operational in magnetic fields of strength up to about 1 Tesla [1, 2, 3]. It is, however, expected to apply much stronger magnetic fields at future collider experiments. We tested a Hamamatsu H2611SXA(24) [4]. This is one of the test pieces of equipment aimed at very high gain, with the number of dynode stages being increased to 24. The parameters of the H2611SXA(24) are listed in Table 1.

HPMT is a new photon-detection device developed by DEP in collaboration with the Canberra, INFN and CERN-LAA projects [5, 6]. It comprises a photocathode and a large-area PIN silicon photodiode, facing very closely to each other in a vacuum. A high voltage is applied between the photocathode and the photodiode so that photoelectrons are electrostatically accelerated for high gain. We tested a commercially available HPMT (PP350B) [7]. The parameters of the PP350B are listed in Table 1. Since a detailed study was reported for prototype HPMT's [6], we report here mainly on the results with magnetic fields of 2.0 and 2.5 Tesla.

VAPD is a hybrid photon-detection device similar to HPMT, which uses a large-area avalanche photodiode instead of a PIN silicon photodiode as the photoelectron detector [8]. VAPD is therefore expected to have a much higher gain than that of the HPMT. Several test results without a magnetic field have been reported [9, 10]. Here, we report on the performance of a VAPD in magnetic fields up to 1.0 Tesla. For the VAPD, we could not apply a magnetic field greater than 1.0 Tesla, due to some magnetic material inside the device. The parameters of the VAPD used in the test are also given in Table 1.

2 Setup

The tests were carried out at KEK, National Laboratory for High Energy Physics. We used two magnets for the tests. One was the 8D320, a normal-conducting bending magnet with a maximum magnetic-field strength of 2.0 Tesla. The other was the SKS, a superconducting spectrometer magnet [11] with a potential magnetic-field strength of 3.0 Tesla. The SKS magnet was under excitation tests at that time, and the available

Parameters	FMPMT	HPMT	VAPD
Photo-cathode diameter	36mm	25mm	18mm
Dynode diameter	36mm	-	-
Anode/Si diameter	36mm	25mm	16mm
PC-Anode/Si distance	19mm	5.6mm	(6mm max)(*3)
max PC voltage	-2.7kV	-8.0kV	-15.0kV
max bias voltage	-	-75V	2250V
Gain w/o magnetic field	1.2×10^8(*1)	1600	1.0×10^5
Quantum efficiency	20% (420nm)	20% (480nm)	23% (450nm)
Rise time	2.1ns(*2)	8ns	9ns

(*1) Gain at -2.0 kV.
(*2) Rise time of commercial tube R2450-09.
(*3) This distance is not controlled at the fabrication process.

Table 1: Parameters of the FMPMT, HPMT and VAPD taken from technical data.

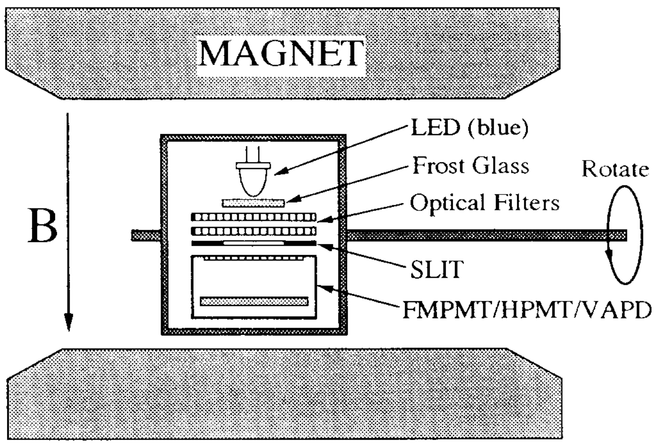

Figure 1: Schematical view of the test setup.

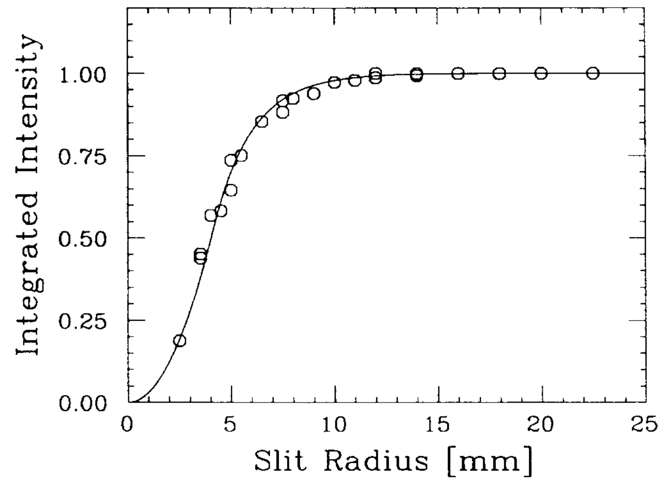

Figure 2: Distribution of LED light on the photocathodes. The solid curve is the parametrized distribution function.

magnetic-field strength was 2.5 Tesla at maximum.

The data at 2.0 and 2.5 Tesla were taken with the SKS magnet, while those at 2.0 Tesla and below were taken with the 8D320 magnet. The data at 2.0 Tesla with the 8D320 magnet were taken during both ramping up and ramping down the magnet to check the reproductivity. Those data show no significant discrepancy as shown in the following sections.

The setup is schematically shown in Fig. 1. A blue LED with a peak emission wavelength of 450nm [12] was directly mounted above the photocathode of a photon-detection device. The same setup was used for all three devices, except for the thickness of the optical filter between the LED and the device. We took data usung a CAMAC charge-sensitive ADC module. No preamps were used.

3 Input photon characteristics

The distribution of LED light on the photocathode was measured without a magnetic field using slits having various diameters. The results are shown in Fig. 2. The solid curve in the figure shows the parametrized function used to calculate the gain-reduction factors described in the following sections.

The number of photoelectrons for the FMPMT was obtained from the width of the pulse-height distribution. The numbers of photoelectrons for other devices were

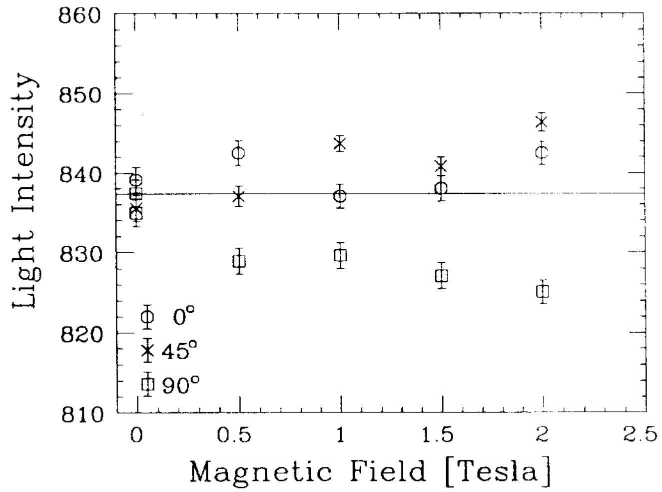

Figure 3: LED light yield versus the magnetic-field strength and angle.

estimated from that for the FMPMT, with the attenuation factor of the optical filter and the quantum efficiencies listed in Table 1.

The pulse-to-pulse fluctuation of the LED light yield was obtained from the width of the pulse-height distribution of the HPMT. In the HPMT measurement, the number of input photons exceeded one million, and thus photon statistics could be neglected. Subtracting the noise contribution from the width, the pulse-to-pulse fluctuation was estimated to be 0.7%, which is negligibly small.

A strong magnetic field may change the light yield of the LED. Leading the LED light through an optical fiber to a PMT located outside the magnetic field, we measured the dependence of the light yield on the magnetic-field strength. The result is shown in Fig. 3. The variation is well within 1.5% for all test conditions, and is thus neglected in the following analyses.

4 FMPMT test

We measured the gain of the FMPMT for various magnetic-field strengths. The tilt angle (θ) between the device axis and the magnetic field was set to be 0° and 35°. The results are shown in Fig. 4. The nominal high voltage (HV) for the FMPMT was 2.7 kV. However, some measurements at low magnetic field were performed with lower HV. The measurements were normalized to the gain at the nominal HV using the known HV-gain

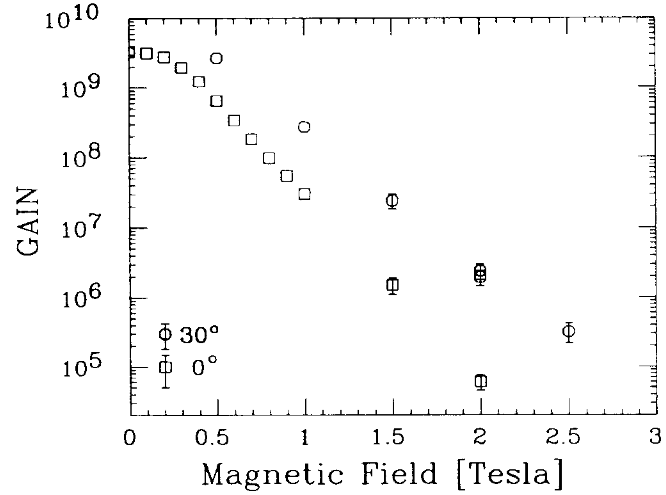

Figure 4: FMPMT gain versus the magnetic-field strength. The data taken with lower photocathode voltages are normalized to the -2.7 kV photocathode voltage.

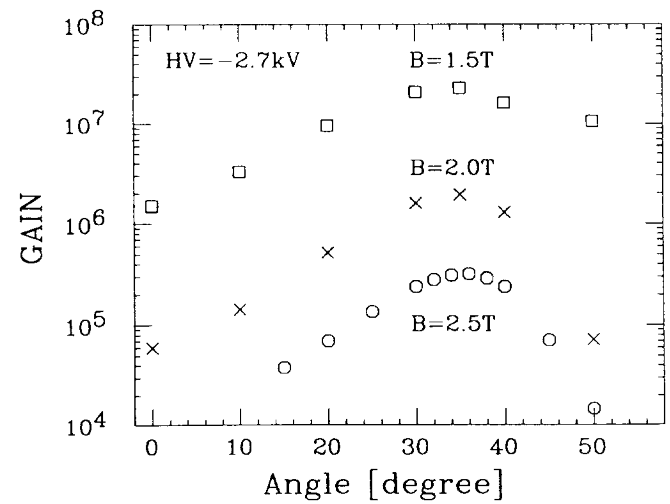

Figure 5: FMPMT gain versus the tilt angle. All of the data were taken with the -2.7 kV photocathode voltage.

relation. The error bars shown in the figure denote the normalization errors. If the magnetic field is parallel to the device axis ($\theta = 0°$), the gain decreases quite rapidly. On the other hand, in the case of $\theta = 35°$, the gain is generally significantly higher, and exceeds 10^5 even at 2.5 Tesla.

In Fig. 5 the gain is plotted for various tilt angles. The gain changes more steeply as the magnetic field becomes stronger. The decrease in the gain at $\theta > 35°$ can be explained by the loss of electrons due to the electron trajectory tilted along the magnetic field. As is easily calculated from the parameters given in Table 1, photoelectrons originating at the center of the photocathode start to miss the anode at $\theta = 40°$. On the other hand, the decrease of the gain at smaller tilt angles can be explained by a self-shielding effect of the dynodes [3]. Secondary electrons emitted from the lower half of a dynode can reach the next stage, while those emitted from the upper half are most likely re-absorbed by the dynode itself. In the case of the axial magnetic field, probabilities that primary electrons hit the lower half of the dynode is the minimum, and that secondary electrons emitted from the upper half of the dynode are re-absorbed is the maximum.

According to the measurements, the required high gain is easily achieved with the FMPMT in a strong magnetic field, if the device axis can be appropriately set with respect to the magnetic field.

5 HPMT test

We measured the gain of the HPMT in various magnetic fields. Figs. 6 and 7 show the gain versus magnetic-field strength and versus the tilt angle, respectively. As expected, no gain reduction was observed for the magnetic field being parallel to the HPMT axis, while a significant gain decrease was observed for $\theta = 60°$.

The gain is reduced in a tilted magnetic field due to two reasons: one is the energy loss of photoelectrons in the surface dead layer of the silicon [6]; the other is the shift of the photoelectron image on the silicon.

The photoelectrons lose their energies before entering the depletion region in the surface dead layer. In order to calculate this energy loss, the thickness of the surface dead layer is estimated from the so-called "turn-on voltage", the minimum photocathode high voltage required to obtain an output signal. We measured the HV-gain relation of the HPMT as shown in Fig. 8, and found the value to be 2.2 kV. Using the electron range given in the particle data [13], the thickness of the dead layer was estimated to be 0.12 μm. For tilted magnetic field, the incident angles of the electrons are no longer normal to the silicon because of cycloid motion, and the energy loss in the surface dead layer increases. Assuming that the electric and magnetic fields are uniform inside the HPMT, exact cycloid orbit equations can be numerically solved. We found that the gain is reduced by 17% for the case of $\theta = 60°$.

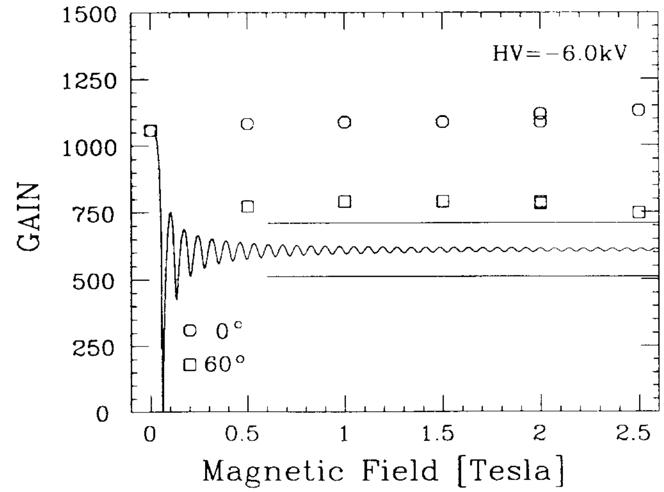

Figure 6: HPMT gain versus the magnetic-field strength. The solid curve is the result of a calculation for 60°, and the solid lines indicate the calculation error.

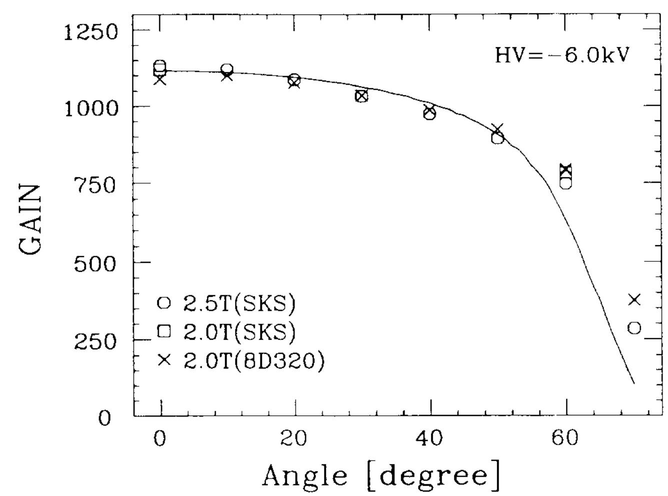

Figure 7: HPMT gain versus the tilt angle. The solid curve is the result of a calculation at 2Tesla.

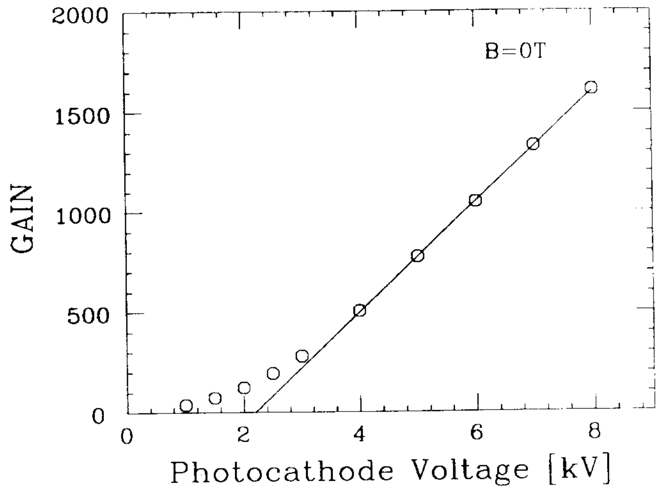

Figure 8: HPMT gain as a function of the photocathode voltage.

The other origin of gain reduction is a loss of photoelectrons due to a shift of the photoelectron image in the magnetic field. From the measured distribution of the LED light on the photocathode, the loss of photoelectrons was calculated to be 22% for the case of $\theta = 60°$. The solid curves in Figs. 6 and 7 are the results of calculations which took into account the two effects simultaneously. Also shown in Fig. 6 is a calculation error, mainly due to the HPMT axis alignment error. The calculation is consistent with the measurement within error, and the behavior of HPMT is roughly explained by these effects.

6 VAPD test

The VAPD has almost the same structure as that of the HPMT, and is expected to work under strong magnetic fields. In Fig. 9 the gain is plotted for a magnetic-field strength up to 1.0 Tesla. Due to some magnetic material inside the VAPD, we could not apply magnetic field more than 1.0 Tesla. In Fig. 10 the gain is plotted for various tilt angles at 0.5 Tesla. For $\theta = 60°$, in contrast with the HPMT case, the gain decreases quite rapidly down to ~1/30 of that without a magnetic field.

Assuming that the electric and magnetic fields are uniform inside the VAPD, the effect of cycloid motion can be calculated. The distance between the photocathode and the APD is assumed to be 6mm, which gives the maximum gain reduction. The turn-on

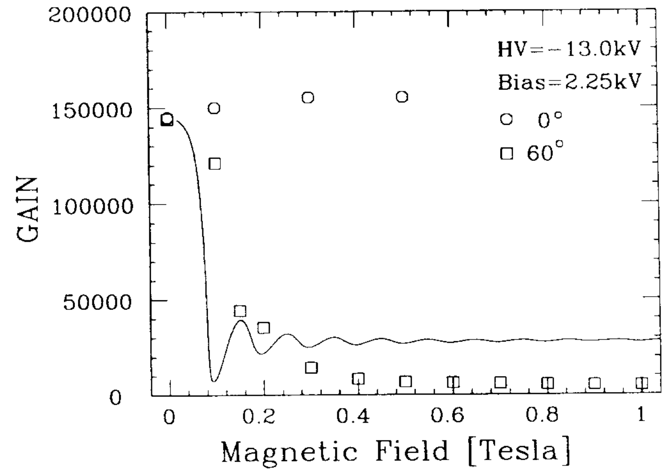

Figure 9: VAPD gain versus the magnetic-field strength. The solid curve is the result of a calculation for 60°.

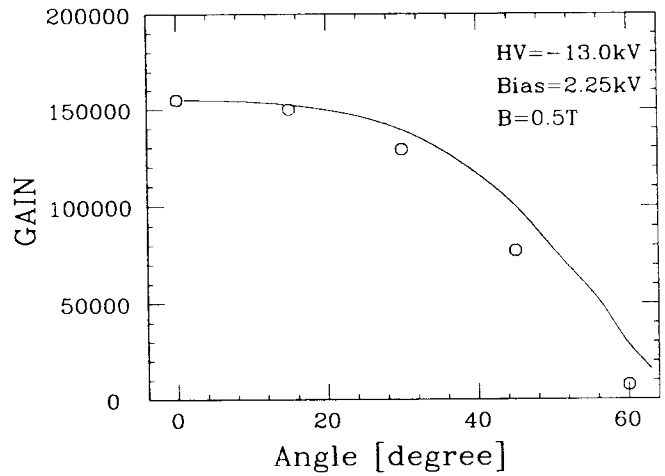

Figure 10: VAPD gain versus the tilt angle. The solid curve is the result of a calculation.

voltage of the VAPD was measured to be 2.2 kV. The gain reduction due to the tilted incident angle was very small because of the high electric field, and was calculated to be only a 6% effect. The effect of the photoelectron image shift was large due to the small APD diameter, and was calculated to be reduced down to 1/6. The solid curves in the figures are the results of a cycloid calculation which took into account the effects of the incident angle and the image shift. However, the measured reduction is much bigger than the calculations, and these effects alone can't explain the behavior of the VAPD. The magnetic material inside the VAPD could be the cause of this discrepancy.

7 Summary

We have tested three types of photon-detection devices in strong magnetic fields. FMPMT and HPMT were found to be operational up to 2.5 Tesla with appropriate field directions, and their behavior is reasonably understood.

The test of the VAPD was rather limited in terms of the magnetic-field strength, and the behavior under a tilted magnetic field is not yet fully explained. However, the device is also operational at least in an axial magnetic field of 0.5 Tesla.

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