Nuclear Instruments and Methods in Physics Research A 827 (2016) 137–144

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Studies of relative gain and timing response of fine-mesh photomultiplier tubes in high magnetic fields

V. Sulkosky [a,*], L. Allison [b], C. Barber [c], T. Cao [c], Y. Ilieva [c], K. Jin [a], G. Kalicy [b], K. Park [b], N. Ton [a], X. Zheng [a]

[a] University of Virginia, Charlottesville, VA 22904, USA
[b] Old Dominion University, Norfolk, VA 23508, USA
[c] University of South Carolina, Columbia, SC 29208, USA

ARTICLE INFO

Article history:
Received 12 January 2016
Received in revised form
20 April 2016
Accepted 30 April 2016
Available online 2 May 2016

Keywords:
Fine-mesh photomultipliers
Magnetic fields
SoLID

ABSTRACT

We investigated the use of Hamamatsu fine-mesh photomultiplier tube assemblies H6152-70 and H6614-70 with regard to their gain and timing resolution in magnetic fields up to 1.9 T. Our results show that the H6614-70 assembly can operate reliably in magnetic fields exceeding 1.5 T, while preserving a reasonable timing resolution even with a gain reduction of a factor of ≈ 100. The reduction of the relative gain of the H6152-70 is similar to the H6614-70's near 1.5 T, but its timing resolution worsens considerably at this high field.

1. Introduction

In nuclear and particle physics experiments, photomultiplier tubes (PMTs) are commonly used to collect photon signals from scintillating detectors. Many such detectors are used for timing measurements, such as time of flight (TOF), which require not only a large signal amplitude, but also a good timing resolution. The timing resolution achieved by the scintillator is directly related to the number of photoelectrons emitted by the PMT's cathode that reduces statistically the timing fluctuation of the PMT's signal due to the scintillator's decay time, the propagation of photons through the scintillator, and the time for the photoelectron(s) to transit from the PMT's cathode to the anode. The performance of scintillators with a PMT readout is highly sensitive to the presence of external magnetic fields because of the field effect on the photoelectrons. For typical PMTs, the trajectory of the photoelectron between the PMT's photocathode and the first dynode is affected by fields as low as a few Gauss, causing a significant loss in statistics and a larger timing fluctuation in the PMT's output [1]. The use of mu-metal shielding can extend the operating range of PMTs up to ≈ 100 Gauss. However, detectors used in modern experiments are often part of large spectrometer systems that include one or more magnets with fields at the Tesla level. To meet the need for operation in Tesla-level fields, special PMTs with fine-mesh type dynodes have been developed and put into use [2,3].

At the Thomas Jefferson National Accelerator Facility (JLab), the Solenoid Large Intensity Detector (SoLID) [4] is being designed to be a large acceptance and a high luminosity device in experimental Hall A. This device is a multi-purpose spectrometer to study physics topics such as semi-inclusive deep inelastic scattering (SIDIS) from polarized targets, threshold J/ψ production, and parity-violating deep inelastic scattering (PVDIS). The SoLID apparatus consists of a solenoid with a magnetic field of approximately 1.5 T and an open-geometry detector package. The PVDIS configuration will consist of one large-angle detector package, while the SIDIS-J/ψ configuration will have two detector packages: one at forward angles and one at large angles. The detector packages for SIDIS will include a set of GEM detectors for tracking, a scintillator pad detector (SPD) for TOF measurements and for trigger-rate reduction by photon rejection, a Multi-Gap Resistive Plate Chamber (MRPC) to provide a TOF measurement at forward angles, a light gas Cherenkov counter to identify electrons, a heavy gas Cherenkov counter for hadron identification, and an electromagnetic calorimeter (EC) for electron identification. For PVDIS, the heavy gas Cherenkov and SPD are not used, otherwise the detector package is similar to that of SIDIS. TOF capability is a critical requirement for the SIDIS experiments. At forward angles, TOF is provided by the MRPC, while at large angles, the Large Angle SPD (LASPD) is the only TOF detector. The LASPD must provide time-of-flight resolution of 150 ps or better, which requires fast, high-photon yield scintillators and fast PMTs. To achieve the required timing resolution, the PMTs need to be

* Corresponding author.
E-mail address: vasulk@jlab.org (V. Sulkosky).

http://dx.doi.org/10.1016/j.nima.2016.04.111
0168-9002/

attached directly to the LASPD bars, which means that the PMTs must operate inside the solenoid field of 1.5 T.

One possible PMT choice for the LASPD is a fine-mesh (FM) PMT with a large effective area, high gain, and small timing jitter. The high-field resistance of these PMTs is achieved by using a fine-mesh dynode structure with layer separation of ≈ 1 mm. The first dynode is a few millimeters from the photocathode, and this small distance allows for efficient collection and multiplication of the primary photoelectrons even in the presence of a high magnetic field. Fine-mesh PMTs date back to the early 1980s and the early designs were based on the studies conducted at that time [5]. Since these early prototypes, the FM-PMT design has matured with various studies conducted over the past few decades [1–3,5–8]. Some of these investigations involved the application to various detector types such as threshold Cherenkov counters [3], which typically have small light yields. These studies aided in the optimization of the number of dynode stages and the mesh spacing, improved magnetic field immunity and absolute gains. However, most of the reported results were limited to magnetic fields less than 1.2 T with only a few measurements up to 1.5 T that only included results on gain and pulse height resolution. The angular dependency of the earlier measurements was also limited for orientation angles with respect to the magnetic field within (0°, 90°). For the SoLID SIDIS program, the available data were insufficient to determine whether FM PMTs would operate reliably and provide timing resolution at the 150 ps level. However based on the earlier studies [7,8], the ideal relative orientation of the TOF PMT's axis with respect to the magnetic field direction in the SoLID setup is projected to be between 30° and 45°. One of the goals of the measurements presented in this paper was to determine the optimal angle for the FM PMTs for use within the SoLID magnet.

We have conducted studies of fine-mesh PMTs' performance in fields up to 1.9 T. The experimental setup is described in Section 2. In Section 3, various experimental and data analysis procedures are discussed. In Section 4, results on the FM PMTs' relative amplitude and timing resolution in magnetic fields up to 1.9 T for a range of orientation angles are presented. Section 5 provides a summary of our study.

2. Experimental setup

All measurements involving magnetic fields presented here were performed in July 2015 using the Jefferson Lab High-B Sensor-Testing Facility in collaboration with Jefferson Lab, Old Dominion University, and the University of South Carolina. The test facility was designed for gain evaluation of small photon sensors in magnetic fields up to 5 T. Additional measurements to characterize the FM PMTs without a magnetic field were conducted at the University of Virginia (UVA) in June and September 2015.

2.1. Fine-mesh photomultiplier tubes

The FM PMTs tested in our study are the R5505-70 (⌀ 25 mm) and the R5924-70 (⌀ 51 mm) from Hamamatsu Photonics [9]. The main properties of these phototubes are presented in Table 1. Both PMTs use a bialkali photocathode with effective diameters of 17.5 mm and 39 mm, respectively. The R5924-70 PMT was delivered as an assembly module H6614-70 without a μ-metal shield. The H6152-70 module was assembled with the R5505-70 PMT, the voltage divider E6133-04 MOD and a 1 mm-thick μ-metal shield, all from Hamamatsu. The effectiveness of magnetic shielding using μ-metal is limited due to saturation effects at $\approx$ 50–100 Gauss [1]. Therefore, since the FM PMTs are tested over a range of fields extending far above 0.1 T, we do not expect the mu-shielding to have much effect on our measurements at the high end of the field range. The results we report here are from tests of one module each of the H6152-70 and H6614-70 assemblies. We operated the modules at a high voltage of +2 kV. A picture of the two assemblies is shown in Fig. 1.

Table 1
Relevant properties of tested Hamamatsu fine-mesh PMTs. TTS stands for the transit time spread.

PMT	R5505-70	R5924-70
Assembly	H6152-70	H6614-70
Diameter (mm)	25	51
Number of stages	15	19
Risetime (ns)	1.5	2.5
Transit time (ns)	5.6	9.5
TTS (ns)	0.35	0.44
Gain at +2 kV	5×10^5	1×10^7

2.2. High field magnet

The superconducting solenoid [10] of Jefferson Lab's High-B Sensor-Testing Facility has a warm bore with length of 76.2 cm and diameter of 12.7 cm. The magnet can reach 5.1 T at 82.8 A, but for this test we only went up to 1.9 T. The central field inhomogeneity is less than 5×10^{-5} over a cylindrical volume that is 5 cm long with a diameter of 1.5 cm. During the measurement period, the magnet was manually refilled with liquid helium from a nearby dewar about every other day.

2.3. Dark box and PMT holder

For the tests presented here, a cylindrical dark box of diameter 11.4 cm and a length of 45.7 cm was used to hold the PMTs. All components of the dark box were non-magnetic. The PMTs were placed one at a time inside the dark box and were held firmly in place with a holder (see Fig. 2) to balance the magnetic torque in case any component of the PMT assembly was magnetic. Fig. 2 shows a picture of a test PMT inside the holder along with definitions of the polar and the azimuthal angles θ and ϕ, respectively, used to describe the orientation of the PMT with respect to the field. Angle θ is the angle between the PMT and the field axes, and ϕ is the azimuthal angle of the PMT with respect to an axis perpendicular to the PMT's axis. The angle θ can be adjusted in 5° increments up to $\pm 60°$ by using a turntable; a positive angle indicates a clockwise rotation about Y (Y'), and a negative angle a counterclockwise rotation. When the angle was changed, the new position was locked into place by tightening a screw into the turntable assembly. For angle ϕ, the orientation was determined by markings on the PMTs outer casing. Due to the imprecision of locating the markings, only rotations in increments of approximately 90° were attempted. The dark box was positioned and centered inside the solenoid's bore by utilizing marks made on the bore's surface, which were previously measured.

The dark box's light tightness was achieved with two endcaps located at each end of the cylinder. One endcap contained a connector located at its center to which a 5-m long optical fiber from Ocean Optics[1] was screwed into place. The optical fiber was used to transport light produced by a light-emitting diode (LED) into the dark box. On the inside of the cap, an 80° diffuser[2] was attached to illuminate the entire surface of the PMT inside the dark box. The other endcap included SHV and BNC feed-through connectors to accommodate the high-voltage and the signal cables. To avoid any potential light leaks, the magnet's bore openings were

[1] P-100-10-UV-VIS.
[2] Edmund Optics #54-506, 25-mm diameter.