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Study of avalanche microchannel photodiodes for use in a scintillating fiber muon beam profile monitor

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Abstract

We report a study on the use of avalanche microchannel photodiodes (AMPDs) with sensitive area $0.75 \times 0.75\,\text{mm}^2$, density of microchannels $10^4/\text{mm}^2$, and maximum gain of 3×10^4, in a scintillating fiber muon beam detector. We show that an AMPD-based detector is efficient for 29 MeV/c muons at count rates up to several MHz and is operational in magnetic fields up to a few Tesla.

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Keywords: Avalanche photodiode; Scintillating fiber; Muon beam

1. Introduction

The μSR [1] spectrometers of the Laboratory for Muon Spectroscopy at the Paul Scherrer Institut in Villigen, Switzerland are fed by beams of polarized muons provided by the Swiss Muon Source (SμS) to study the properties of condensed matter. Setting-up and optimization of the performance of the spectrometers requires a detector capable to measure the profiles of high intensity non-relativistic muon beams and to be operational in high magnetic fields.

These requirements can be met in a multichannel detector realized as a grid of scintillating fibers spaced along the x and y directions perpendicular to the beam axis z. Such a detector probes the beam intensity at coordinates x_i and y_j of the fibers or at fiber intersection points (x_i, y_j). As photosensors for the fiber readout one could consider multianode photomultiplier tubes (PMTs) or avalanche photodiodes. The operation of a PMT-based device in a high magnetic field would require the use of long fiber light guides and would make the device quite bulky. Avalanche photodiodes (APDs) are known to be insensitive to magnetic fields [2] and, therefore, allow a much more compact design of the device. The APDs produced nowadays range from the linear-mode devices with characteristic values of gain ~100 to the Geiger-mode multipixel APDs with pixel density $\sim 10^3\,\text{mm}^{-2}$ and gain $\sim 10^6$ [3].

An Avalanche Microchannel Photodiode (AMPD) of type R8 [4] developed in the Joint Institute for Nuclear Research in Dubna, Russia, is a Geiger-mode device with a microchannel (micropixel) density of $10^4\,\text{mm}^{-2}$. Its main features are a high photon detection efficiency (~15% at 430 nm) and a rather high ($\sim 3 \times 10^4$) maximum gain [3].

In this work, we study the performance of a scintillating fiber detector module based on a $0.75 \times 0.75\,\text{mm}^2$ active area AMPD for detection of 29 MeV/c muons in magnetic fields up to 4.8 T and at the event rates up to $10^7\,\text{s}^{-1}$.

2. Measurements

The high gain of the AMPD allows to use it with a fast voltage-sensitive amplifier. The amplifier scheme (see Fig. 1) is based on the MAR monolithic amplifiers from mini-circuits [5]. The amplifier has a gain of ~250, bandwidth ~250 MHz, and input impedance ~200 Ω. The AMPD is mounted directly on the amplifier board in order to minimize the noise pickup. A test detector module was

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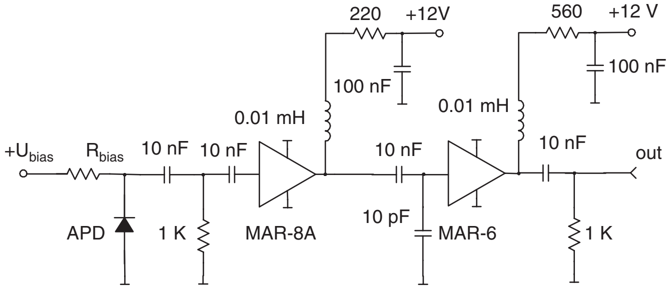

Fig. 1. Scheme of the broad-band amplifier for use with an AMPD.

build by coupling a 70 mm long 1 mm × 1 mm square cross-section BCF-10 scintillating fiber [6] (peak emission at 432 nm) directly to the AMPD. The detector was placed at the center of a 5 T superconducting solenoid (warm bore diameter 20 cm, length 1 m) set up in the πE3 muon beam line of the SμS. For recording and analyzing the detector signals a Lecroy WavePro 960 digital oscilloscope was used. All the measurements were performed at a bias voltage $U_{\text{bias}} = 101.5\,\text{V}$ with a biasing resistor $R_{\text{bias}} = 20\,\text{k}\Omega$. The oscilloscope screenshots for the $1e$ (dark) and muon (μ) signals are shown in Fig. 2. The gain of the AMPD is high enough to increase the $1e$-pulse height above the amplifier noise level.

Fig. 3 shows the amplitude distributions of $1e$ and muon signals obtained in zero and 4.8 T magnetic fields. The average number of photoelectrons created per muon hitting the fiber of about 55 is deduced from the ratio A/A_{1e}, where A and A_{1e} are the mean values for the muon and $1e$ signal amplitudes. (Note that there is a 50% light loss due to the mismatch of the AMPD active area and the fiber cross-section.) The amplitudes of the muon as well as of $1e$ signals decrease slightly (by about 10%) in 4.8 T magnetic field as compared to zero field. This effect is attributed to the change of the performance of the amplifier, rather than of the AMPD, in the magnetic field: about the same field dependence of the amplifier output signal was observed when the input signal was provided by a pulse generator.

The maximum muon rate per fiber in these measurements was $6 \times 10^5\,\text{s}^{-1}$. At this rate the signal amplitude A decreases by about 10% compared to its value A_0 at low rates ($\leqslant 10^4\,\text{s}^{-1}$), see Fig. 4a. The rate dependence of the signal amplitude is due to the fact that the gain M of each single pixel of the detector depends on the rate n_1 of pulses counted by this individual pixel (the $1e$ pulses). The following factors contribute to the $M(n_1)$-dependence: (a) DC voltage drop on the biasing resistor (this effect can be minimized by choosing a small value of R_{bias}); (b) finite "recovery" time of the pixel [7], i.e., the time required to recharge the pixel capacitance following the $1e$-pulse. Provided the dependence $M(n_1)$ is known, the value of M can be predicted for signals with amplitude A and rate n, based on

$$n_1 = n_{1,0} + n(A/A_{1e})N_{\text{pix}}^{-1}, \tag{1}$$

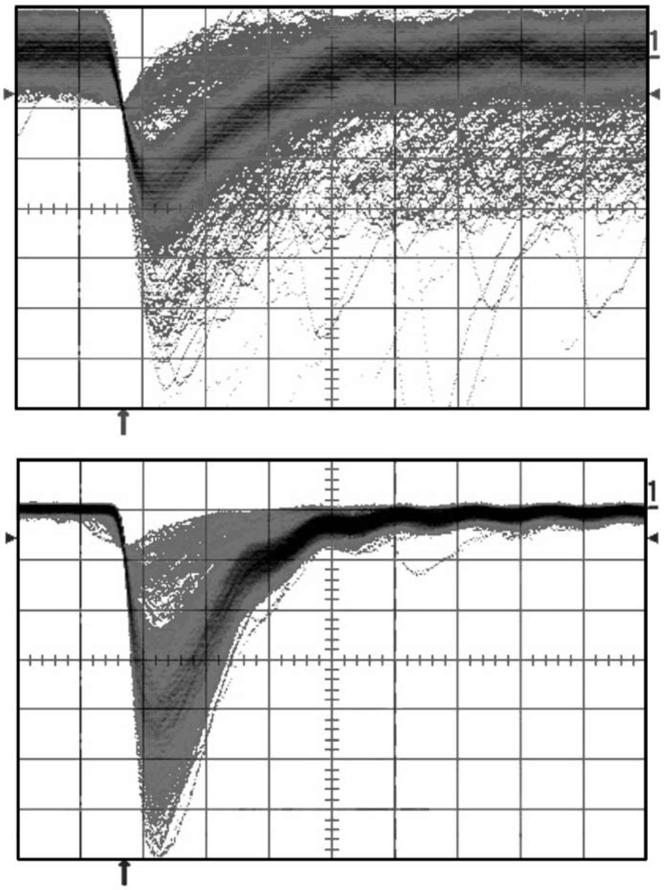

Fig. 2. Oscilloscope screenshots of $1e$ signals (top: horizontal scale is 5 ns/div, vertical scale is 5 mV/div) and muon signals (bottom: 10 ns/div, 100 mV/div).

where $n_{1,0}$ is the minimum ("dark count") rate of pulses per pixel at a given temperature; A_{1e} is the amplitude of $1e$-pulses; the ratio A/A_{1e} gives the number of photoelectrons per pulse of amplitude A; $N_{\text{pix}} = 5625$ is the total number of pixels per sensitive area of the AMPD.

The dependence $M(n_1)$ was measured as follows. First the AMPD current I caused by illumination with continuous light of a given intensity was determined. Then the amplitude A of the (amplified) AMPD output signal at this given current was measured by additionally illuminating the AMPD with a pulsed LED of repetition rate 1 kHz and an amplitude $A \ll A_{1e} \cdot N_{\text{pix}}$ (i.e., generating much less than one photoelectron per pixel). For biasing and measurement of the AMPD current a KEITHLEY 6487 picoammeter-voltage source was used. The temperature during the measurements was about 15 K above room temperature due to power dissipation in the amplifier circuits. The rate of $1e$ pulses per pixel then is obtained as

$$n_1 = I/(eMN_{\text{pix}}), \tag{2}$$

where e is the electron charge; $M = M_0 \cdot (A/A_0)$, M_0 and A_0 are the values of the gain and the signal amplitude at $I = I_0$ (I_0 is the dark AMPD current). At $I \sim I_0$ the gain was determined as $M_0 \approx 1.7 \times 10^4$.