Application of Avalanche Photodiodes for Scintillating Fiber Readout

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Abstract: We are investigating the application of avalanche photodiodes (APD's) for readout of the signals of a scintillating fiber tracker for the CDF experiment at Fermilab. The unit of the tracking device is a 3HF fiber doublet which consists of layers of 0.5 mmϕ fibers stacked with stagger by half a fiber diameter. Each APD array has 16 pixels of 1 mmϕ arranged in line. We tested the performance of the APD array using a conventional charge amplifier and shaping amplifier. In order to optimize the S/N ratio, we measured the signal and the noise as a function of the temperature and of the bias voltage. In the temperature range from -55 to $+20$°C, the S/N ratio was measured to increase with lowering the temperature. At temperatures below -20°C, an S/N ratio of better than 10 is achievable for ~ 50 photons expected from the 3HF fiber doublet.

1. Introduction

Intensive R&D on the fiber tracking system is being carried out in order to upgrade the CDF detector at Fermilab [1]. For the RUN II data taking run [1] scheduled to start in 1999, the present VTPC (vertex time projection chamber) is replaced with a scintillating fiber tracker to cope with the short beam crossing, 396 ns at beginning and 132 ns later, and the 10-fold increased luminosity of $\sim 2 \times 10^{32}$ cm^{-2}s^{-1}.

The fiber tracking system (IFT, intermediate fiber tracker) is composed of about 50,000 fibers of 0.5 mm diameter and 2.2 m length. The baseline photodetector of the IFT is a VLPC (visible light photon counter) which can detect signals to a single photon level. VLPC's function at liquid He temperature, therefore the scintillator signals are brought outside the tracking volume to a He cryostat system using about 5 m long clear optical fibers.

We are optimizing the fabrication method of scintillating fiber bundles. Application of APD's is under investigation for the fiber signal readout for use in RUN III. In RUN III where a much higher luminosity is foreseen, a scintillating fiber system with fast response will be a natural candidate for the central tracker. One of the key issues to this application is a compact readout system where *e.g.* APD's are coupled directly to the fibers and fast readout electronics system located nearby keeps the hit information in pipelines as well as produces trigger signals. Such a compact photodetector and electronics system is essential, otherwise millions of fiber signals have to be extracted from the central tracker.

We are testing APD's fabricated by Hamamatsu Photonics. APD's are interesting for fiber signal readout because of the compactness and the ability of signal multiplication of 100-300. APD's show relatively large noise levels, which has limited their application for readout of weak signals. Our attempt is, along with efforts in reducing the dark current of the APD's in collaboration with the manufacturer, to look for the operation conditions where the signal-to-noise ratio is better than $\sim$10 for the signal level expected from our fiber system. The parameters investigated were the bias voltage and the temperature. As the bias voltage is set close to the breakdown voltage the dark current increases rapidly, and hence the S/N ratio is degraded. The APD multiplication increases with decreasing the temperature. This phenomenon is explained by phonon-electron scattering [2], the scattering probability being smaller at lower temperatures. Because of this feature, we can lower the bias voltage at lower temperatures while maintaining the same APD gain and reducing the noise level.

In section 2 we briefly describe the scintillating fiber system. The performance tests of APD arrays are covered in section 3. Section 4 summaries the results.

2. Scintillating fiber system

The basic unit of the fiber tracker system is a two-layer fiber bundle, each layer being staggered by 0.3 mm, as shown in Fig. 1. Each layer consists of 0.5 mmϕ 3HF scintillating fibers arranged with a lattice spacing of 0.6 mm. We use Kuraray multiclad scintillating fibers [3] with 1% p-terphenyl and 1500 ppm 3HF (3-hydroxyflavone) concentrations. The lattice spacing is set larger than the fiber diameter so that the variation of the fiber diameter, about 10 μm at maximum, will not be accumulated within the fiber bundle. In the current IFT design, the fiber bundles so position controlled are mounted on a cylindrical structure parallel (Z-fibers) to the beam direction at six radial positions from 18 cm to 27 cm, and U-V fiber bundles with angles $\sim \pm 5°$ relative to the Z are located at three radial positions. The bundles are fixed to low-Z structures (*e.g.* Rochacell) using epoxied carbon fiber cloths. The fiber length is 2.2 m covering a pseudorapidity range up to 2. The diameter of the scintillating fibers of 0.5 mm is determined from the hit occupancy and the requirement on the light yield. The hit occupancy at the highest luminosity $2\times10^{-32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is about 5% for the innermost layer.

In the measurements at University of Tsukuba, we used fiber bundles consisting of 2×16 fibers. The 32 fibers are coupled to a phototube through a lucite light mixer. In order to simulate the measurement with VLPC's, some data were taken with the 32 fibers connected to 5 m long 0.6 mmϕ clear optical fibers. The phototube, Hamamatsu R2257, has a red-sensitive photocathode whose quantum efficiency is 9–10% in the spectrum range of the 3HF emission. A ^{90}Sr source with a 2 mmϕ collimator is set above the bundle and the penetrating β particle is triggered with a scintillating counter set underneath. The source and trigger system is moved along the fiber bundle by a stepping motor.

The light yields are shown in Fig. 2 as a function of the source position to the phototube, where the data are compared with and without the Al mirror at the 3HF fiber ends. The mirror can almost double the light yield near the mirrored end, and make the attenuation length longer. The number of photons, corrected for the phototube quantum efficiency, is 46 at a distance 1.1 m from the phototube. The light yield is minimum at 1.1 m along the fiber because the path length increases at longer distances due to the angle of the tracks. Therefore the number of photons 46 is a good value for evaluation of the APD performance with our scintillating fiber tracker. When connecting to 5 m clear fibers for the case of readout with VLPC's, the light yield decreases by a factor of 3 and is 15 photons at a distance of 1.1 m.

3. Performance of the APD

16-channel APD arrays are fabricated by Hamamatsu Photonics. We made two types of arrays. One with pads 1 mmϕ arranged in line at a 1.6 mm spacing, and another with pads 1 mm square at a 1.1 mm spacing. Typical capacitance values are 4 pF for round pads and 7 pF for square pads at a bias voltage of around 300 V corresponding to a multiplication gain of 100. The breakdown voltage where the dark current exceeds 0.1 mA is about 20 V higher than the bias voltage corresponding to a gain of 100.

The setup for the measurements of the APD S/N ratio is shown in Fig. 3. The APD and the preamplifier [4] are placed in a thermostat chamber. The signal out of the preamplifier is extracted through a 20 m long coaxial cable and fed to a shaping amplifier [5]. The signal shape is read out with a digital scope. The hybrid preamplifier has a sensitivity of 30 V/pC, and the shaping amplifier has a shaping time of 150 ns. We used a scintillating tile/fiber system as the light pulser. β-rays penetrating the 4 mm thick scintillator plate are triggered by a scintillation counter set underneath. A 3HF wavelength shifting fiber embedded in the tile absorbs the scintillating light and re-emits longer wavelength light. Thus uniform light output can be obtained from the fiber end compared to the case using a round fiber. The light output is set to 47 photons by adjusting the fiber length embedded in the tile. The light yield 47 photons is the light yield expected when the APD is coupled directly to the 3HF bundle as mentioned before.

The results obtained for a round APD array are shown in Fig. 4 where the signal heights and rms noise values are plotted as a function of temperature. The bias voltages were adjusted so that the signal height was measurable in our system. The pulse height increases with decreasing the temperature. The rms noise level, on the other hand, stays almost constant at the same bias voltage. The S/N ratio measured for 47 photons improves with decreasing the temperature as shown in Fig. 5. The S/N of 10 is achievable at $-20°$C.

The APD gain was measured using a DC light source by comparing the signal current to that when no bias voltage was applied. At a gain of 100 the signal height of 47 photons corresponds 38 mV in our measurement system. As can be seen in Fig. 4, a gain of $\sim$300 was obtained without deteriorating the noise level. At around $-20°$C, the temperature dependence of the gain was $-5\%/°$C and the voltage dependence ranged from $+10\%$/V (gain=77) to $+18\%$/V (gain=310).

4. Summary

We have tested an APD array for application in a scintillating fiber tracker readout. For the light yield of about 50 photons per particle, evaluated for 3HF doublet bundles, an S/N ratio of 10 can be achieved if the APD is cooled down to $-20°$C. The gain stability is $-5\%/°$C against temperature and $\sim+15\%$/V against voltage variations.

We are currently investigating a new type of APD's [5] being developed by Hamamatsu Photonics whose dark current level is claimed to be substantially reduced compared to the present type of APD's.

References

[1] CDF Collaboration, "Physics with CDF in Run II"; CDF Collaboration, "The CDF Upgrade", CDF-note 3171

[2] G. A. Baraff, Phys. Rev. 128 (1962) 2507; C.R. Crowell and S.M. Sze, Appl. Phys. Lett 9 (1966) 242; S. Kobayashi et al., Nucl. Instr. and Methods A 364 (1995) 95.

[3] see, for example, S. Aota et al., Nucl. Instr. and Methods A 357 (1995) 71.

[4] Digitex Laboratory Co., Ltd. HIC-1576; see also T. Taniguchi, Y. Fukushima, and Y. Yoribayashi, IEEE 1988 Nuclear Science Symposium, Orlando, Florida, Nov. 9-11, 1988.

[5] Hohshin Denshi Co., Ltd. Model N012.
[6] The APD described in the text is Hamamatsu S4055. The new type is S5343.

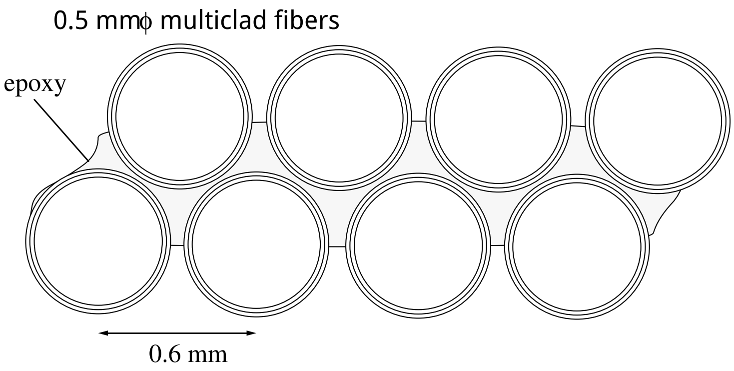

Figure 1: Towers of the plug tile-fiber calorimeter. The scale is for The structure of the fiber bundle, consisting of two layers of 0.5 mmϕ 3HF fibers.

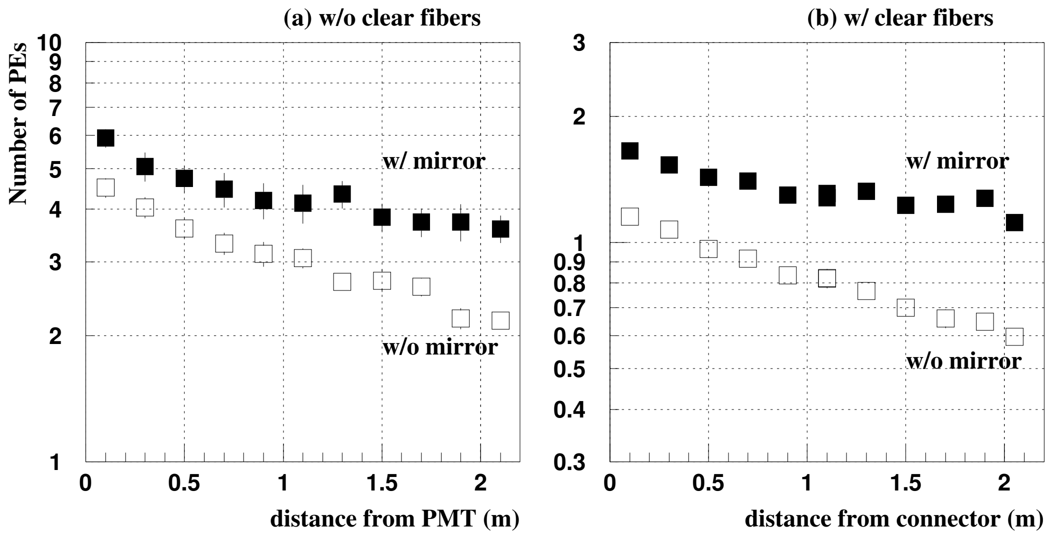

Figure 2: The light yield measured with a phototube with QE=10% as a function of the source position along the fiber doublet (a) without extra clear fiber connected and (b) with 5-m long clear fibers connected.

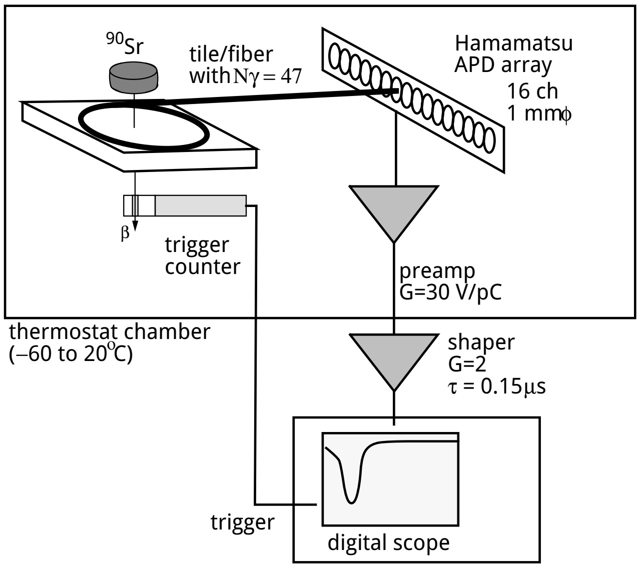

Figure 3: The schematic diagram of the measurement system. The temperature of the thermostat chamber was varied from $-60°$ to $30°$.

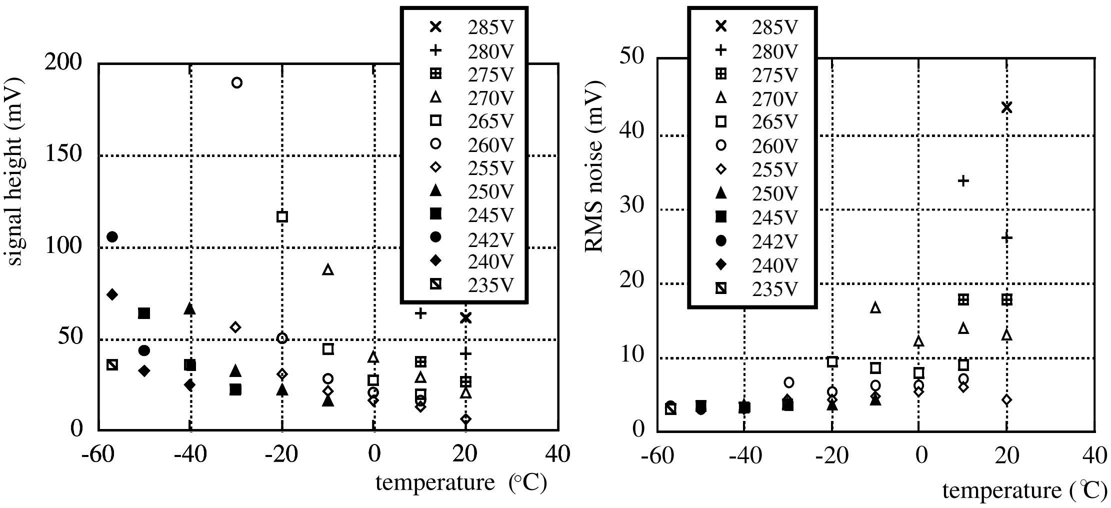

Figure 4: (left) The average signal height and (right) rms noise level as a function of the temperature. The data are shown for different settings of the bias voltage.

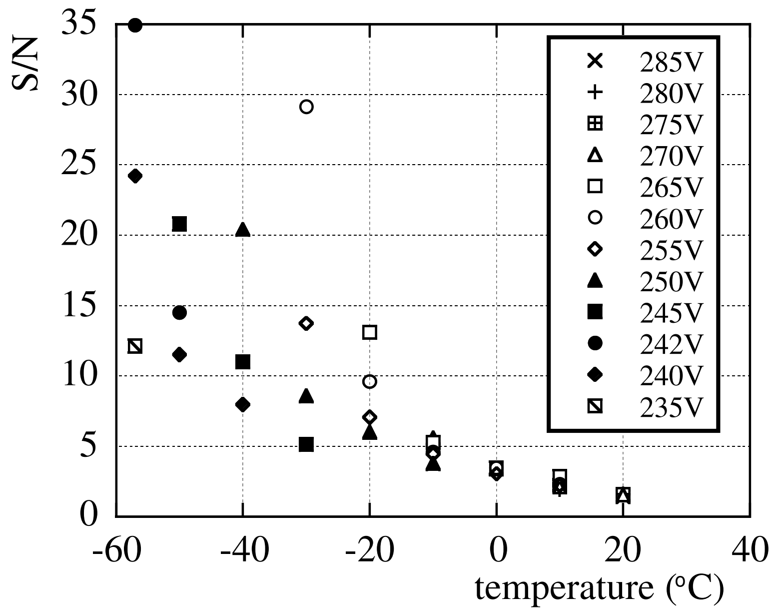

Figure 5: The signal-to-noise ratio as a function of the temperature. The data are shown for different setting of the bias voltage.