Received: *April 14, 1999*, Accepted: *September 21, 1999*

Application of avalanche photodiodes as a readout for scintillator tile-fibre systems

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Abstract: The application of reach-through avalanche photodiodes (R'APD) as a photodetector for scintillator tiles has been investigated. The light collected by WLS fibres (0.84 mm and 1 mm diameter) embedded in the scintillator has been transmitted to the 0.5 mm^2 active surface of APDs by clear optical fibres and optical connectors. A low noise charge sensitive preamplifier ($\approx 400e^-$ equivalent noise charge) has been used to gain the photodiode signal. Various configurations of tile-fibre systems, suitable for CMS and LHCb experiments at LHC have been studied using cosmic muons and muon beam at SPS at CERN. In order to optimize the performance of APDs, measurements in the temperature range from -10^o C to $+25^o$ C have been done. The MIP detection efficiency and e^-/MIP separation have been estimated in order to determine applicability of the readout for LHCb preshower.

Keywords: Hadron-Hadron Scattering.

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JHEP09(1999)022

Contents

1. Introduction

During the last years, an active R&D on calorimetry systems using scintillator tile-fibre readouts is being carried out in the framework of design and construction of the new detectors for LHC accelerator [1, 2]. The physics goals and conditions at LHC impose certain requirements on the active elements of the calorimeters, in particular:

- Operation in magnetic field up to 4 Tesla.
- Large linear dynamic range — 10^5 for the detector–preamplifier couple.
- Long lifetime of the photodetectors — 5 to 10 years of operation at high luminosity.
- Radiation hardness — up to 2 Mrad integrated dose.
- Small size — because of very large number of channels in use.
- Sufficient Signal/Noise ratio — to measure the signal from a minimum ionizing particle (MIP).
- Capability of measuring the signal generated by a radioactive source as a DC current to a precision of 1%.
- Reasonable price.

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Two main types of photodetectors satisfy the above conditions: hybrid photodiodes (HPD) and avalanche photodiodes (APD). The advantages of avalanche photodiodes over the other types of photodetectors are:

- Insensitivity to magnetic field.
- Linear dynamic range of 10^6.
- Fast response ($< 1\,\mathrm{ns}$).
- High quantum efficiency in the range from 200 nm to 1100 nm.
- Small size ($10 \times 10 \times 5\,\mathrm{mm}^3$).
- Low price of the APD and preamplifier.

Possible disadvantages of the APDs are the low internal gain ($50 - 300$) compared to the photomultipliers and HPDs and the relatively high excess noise factor.

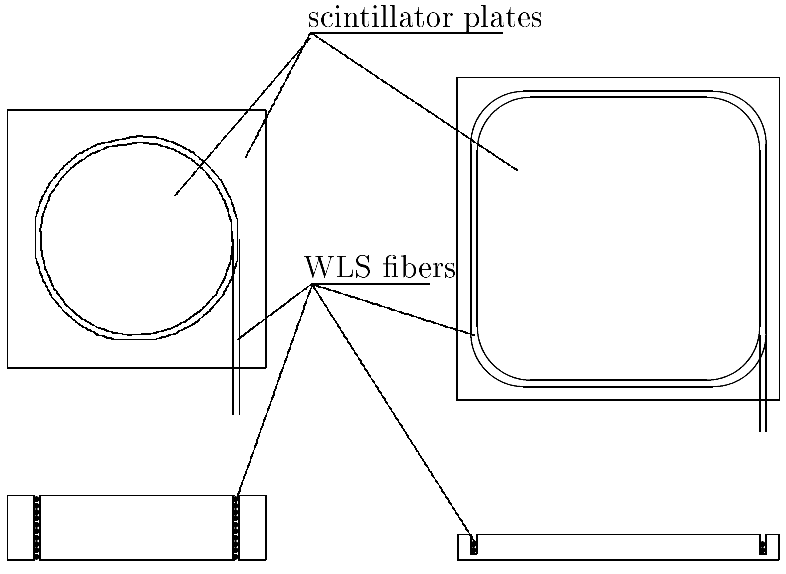
The present paper is devoted to the investigation of the applicability of APD as a readout for scintillator tile-fibre systems. The choice of the scintillator tiles design has been determined by the requirements for two of the LHC experiments under preparation, CMS and LHCb. The main goal of our research was to achieve a Signal/Noise ratio sufficient to measure the MIP signal from scintillator tile–fibre and good e^-/MIP separation needed for the preshower detector of the LHCb experiment. For this purpose, various designs of the scintillator tile-fibre system have been developed (section 2). The APD's characteristics, electronics and calibration of the systems under investigation are presented in sections 3, 4 and 5 respectively. The results from measurements performed with cosmic muons and muon beams at SPS accelerator are reported in section 6.

It is shown that cooling of the photodiodes reduces the dark current and increases the gain thus allowing us to achieve by times higher Signal/Noise ratio and to reach our goal.

2. Scintillator tile–fibre system

Two different designs of scintillator tile–fibre system have been studied (fig. 1). The first one is under investigation for the preshower detector of LHCb experiment [4] while the second one is proposed for CMS HCAL [3].

The scintillator used in our measurements has been produced in Kharkov with characteristics close to that of Kuraray SCSN-81. The scintillator light has been collected by wavelength shifting (WLS) fibres embedded in the tile. The scintillator surface on which the WLS fibres are placed has been matted. As a result, a 20% increase of the light yield has been obtained. Three different types of WLS fibres



(*a*) (*b*)

Figure 1: Two designs of the scintillator tile - fibre system. (a) scintillator size $4 \times 4 \times 1$ cm^3; (b) scintillator size $22 \times 22 \times 0.4$ cm^3.

Tile-fiber configuration	Light yield, ph.e.
$22 \times 22 \times 0.4$ cm^3 scintillator with 1 coil of Bicron 91A fiber	4.0
$22 \times 22 \times 0.4$ cm^3 scintillator with 3 coils of Bicron 91A fiber	7.8
$4 \times 4 \times 1$ cm^3 scintillator with 8 coils of Bicron 91A fiber	11.1

Table 1: Average number of photoelectrons induced by cosmic muons.

— green Kuraray Y11/0.84 mm diameter, green Bicron 91A/1 mm and red Bicron 99-172/1 mm have been used in our measurements.

Outside the tile, the WLS fibre has been coupled to a clear fibre via a specially designed optical connector [4]. The light output loss in the connector has been estimated at the level of 25%.

In order to measure the scintillators light output, induced by cosmic muons we coupled WLS fibres directly to the PMT (FEU85) window. The signal from PMT was read out by charge- sensitive ADC LeCroy 2249W with 250 fC/channel sensitivity using a 160 ns gate, triggered by two other scintillator counters. Calibration of PMT was done by fitting the single photoelectron distribution, produced by 15 ns light pulses of blue LED using the method proposed in [5]. The average number of photoelectrons induced by cosmic muons is presented in table 1. Taking into account the PMT photocathode quantum efficiency at 500 nm emission peak of green WLS fibers ($\approx 10\%$) [6] we have estimated ≈ 100 photons from $4 \times 4 \times 1\,\mathrm{cm}^3$ scintillator with 8 coils of fibre.

3. Avalanche photodiodes

The particularity of APDs over photomultipliers, is the noisy amplification process. In the APD the avalanche multiplication is a random process leading to additional fluctuations in the collected charge. These fluctuations are characterized by the excess noise factor F. The latter is related to the amplification of holes and electrons and can be approximated by the expression:

$$F = k \times M + \left(2 - \frac{1}{M}\right) \times (1 - k),$$

where k is the ratio of the ionization coefficients of holes and electrons and M is the APD's gain. These fluctuations lead to the r.m.s. broadening of the signal given for N_{pe} photoelectrons by $\sqrt{F/N_{pe}}$. Another source of noise and deterioration of the energy resolution is the leakage current. It can have two sources: surface and bulk current. The surface leakage current does not undergo multiplication whereas the bulk current generated in the amplification region does, giving an additional contribution to the smearing of the signal distribution depending on M.

In order to obtain the best possible signal to noise ratio S/N we have to reach a compromise between a high gain and a reasonable noise level. For bias voltages close to the breakdown one (high gain) the excess noise factor and leakage current increase rapidly, and hence the S/N ratio is degraded.

The way to work with high gain, keeping at the same time the noise at a reasonable level is to lower the temperature of the APDs. The APD's multiplication increases with decreasing the temperature. This phenomenon is explained by photon-electron scattering [10], 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's gain and reducing the noise level.

The avalanche photodiodes under investigation are manufactured by InterQ Ltd. using planar technology on a $p-$type high resistivity silicon with a resistivity of $2k\Omega\,\text{cm}$ [7, 8]. They are $n^+ - p - \pi - p^+$ type (R'APD).The multiplication region of the diodes is produced by ion implantation and two- stage diffusion of boron and phosphorus (fig. 2). The active surface of the detectors is $0.5\,\text{mm}^2$. Some characteristics of the diodes are presented in table 2.

Thickness [μm]	140
Active dia. [mm]	0.8
Capacity [pF] at $100V$	0.92
Breakdown voltage [V]	$250 - 380$
Dark current [nA] at $100V$	< 1

Table 2: Avalanche photodiode characteristics at room temperature.

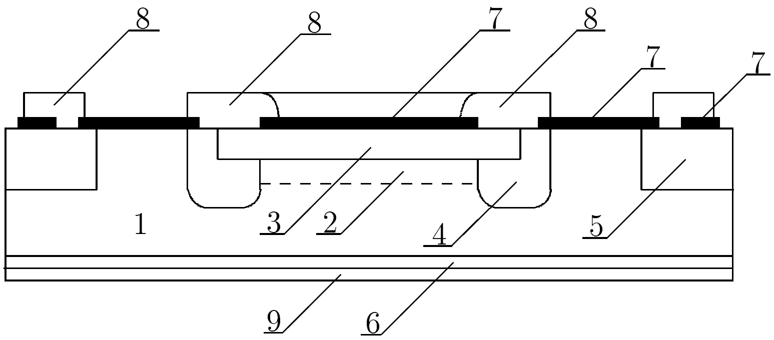


Figure 2: A transverse view of the avalanche photodiode. (1) high resistivity $p - Si$; (2) $p-$region; (3) $n^{+}-$region; (4) $n-$region; (5) $p^{+}-$region; (6) $p-$region; (7) dielectric cover; (8), (9) metal layers.

4. Electronics

The schematic view of the specially designed for our investigation electronics is presented on fig. 3.

The chain consists of a charge-sensitive preamplifier, CR–RC shaper and current feedback amplifier, which can drive a back terminated 50 Ω line. A JFET SST309 transistor with high forward transconductance (determined by the very short shaping time, 25 ns) about 15 mS per 10 mA drain current and a relatively low input capacity, 6 pF, was used. The noises of the shaping amplifier become significant (the noise bandwidth is 10 MHz) due to the short shaping time. For this reason, microwave bipolar transistors with low $R_{BB'}$ ware used. The thermostability of the preamplifier was achieved via negative feedback.

The main parameters of the preamplifier are:

- Equivalent charge noise $\approx 400e^{-}$ at $1pF$ detector capacity (fig. 4).
- Sensitivity of the preamplifier $160\,\mathrm{mV}/10^{6}e^{-}$. (This coefficient depends on value of the capacitor $C1$.)
- 25 ns shaping time.
- Full width of output signal ≈ 150 ns.
- Maximum output voltage about 3.5 V.

5. Calibration of the readout

In order to find the APD's best operation conditions we have investigated the dependence of the gain, noise and S/N ratio on the bias voltage and temperature.

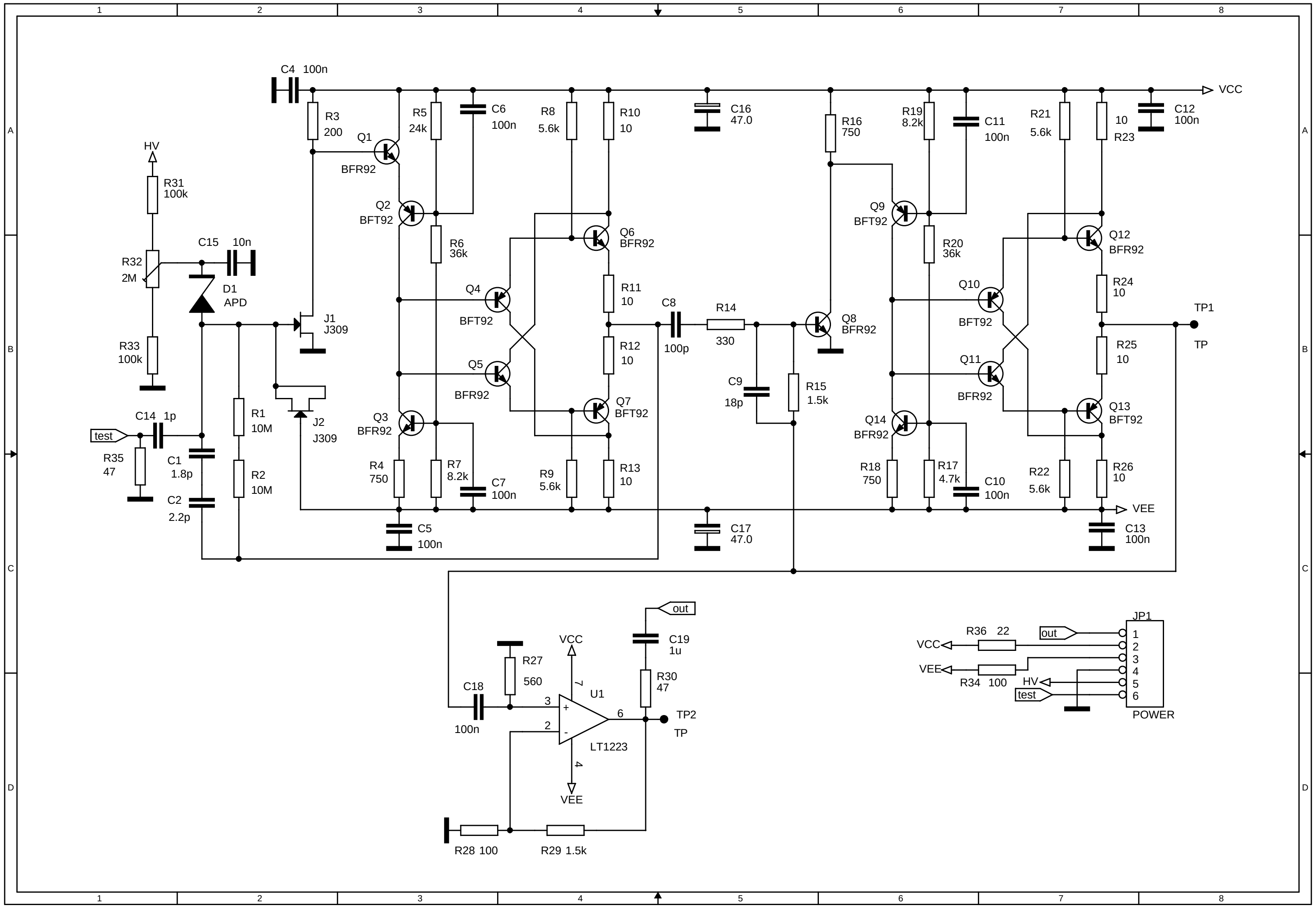


Figure 3: Schematic view of the electronics.

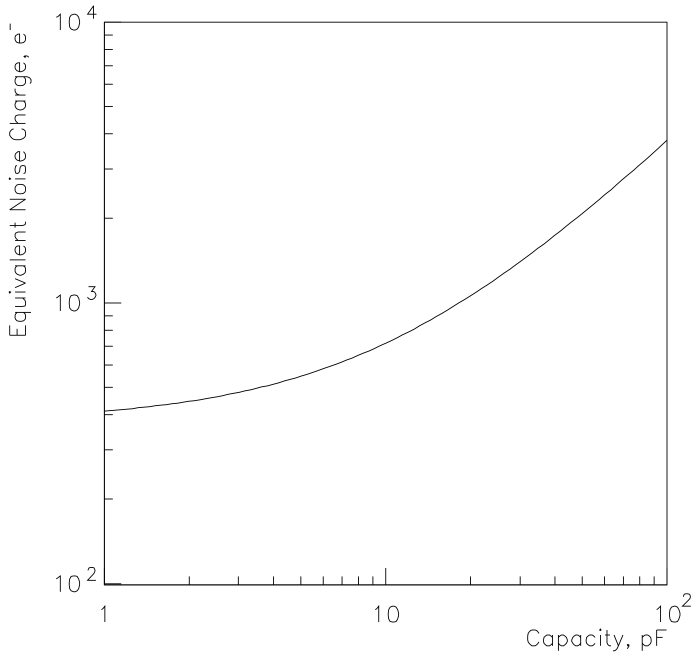


Figure 4: The equivalent noise charge of the preamplifier as a function of the detector capacity.

Calibration of the APD readout has been done using 15 ns long blue light pulses emitted by LED. The light has been split up between APD and calibrated PMT (see section 2) readouts. The APD and preamplifier were placed in a temperature-controlled chamber. The signals from both readouts have been digitized by qADC with 160 ns gate.

The measurements have been done at different light intensities, reverse bias voltages and temperatures. The signal is determined as a mean value of the corresponding distribution. The noise of the APD and preamplifier has been measured using r.m.s. of the pedestal distributions. The summary results are presented below:

- The internal gain of APD, normalized to the gain at 60 V and 22^o C, as a function of applied bias voltage at different temperatures is shown on fig. 5. Cooling of the photodiodes leads to a breakdown voltage decrease and to a valuable gain increase mainly at voltages near to the breakdown.

- The APD and preamplifier noise in terms of ADC channels vs. applied bias voltage is plotted on fig. 6. At low temperatures the noise remains low up to a particular voltage near to the breakdown and then increases drastically. On the other hand, at high temperatures noise is higher and increases smoothly with the bias voltage applied. The equivalent noise charge can be estimated taking into account that the preamplifier gain is $68e^-$ per ADC channel. The small increase of the noise at low bias voltages is due to larger capacity of photodiodes because at these voltages there is no full depletion of charges.

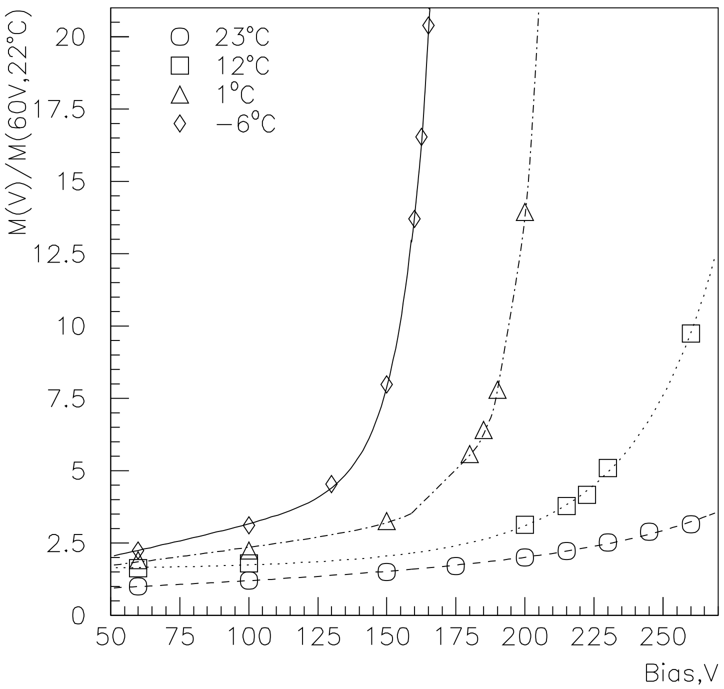


Figure 5: The APD's gain normalized to the gain at $60V$ and 22^o C as a function of the applied bias voltage at different temperatures.

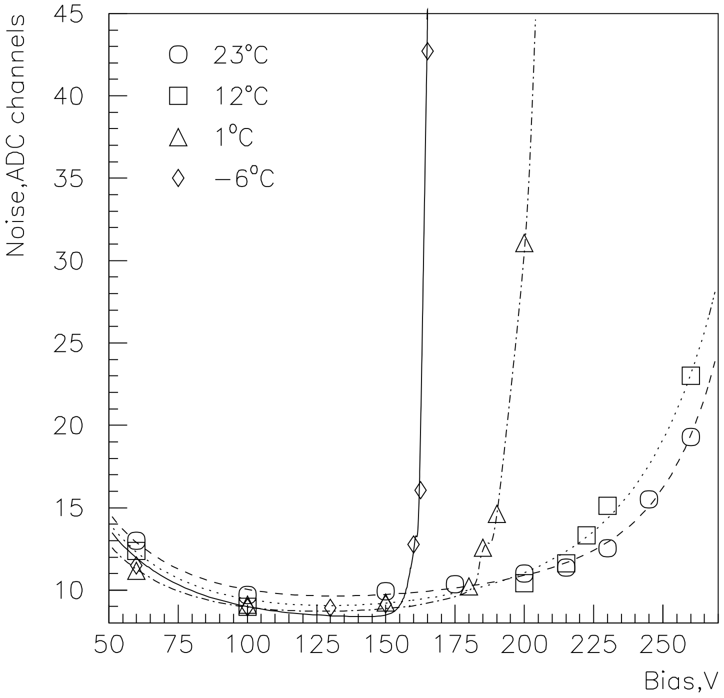


Figure 6: The APD's and preamplifier noise RMS as a function of the applied bias voltage at different temperatures.

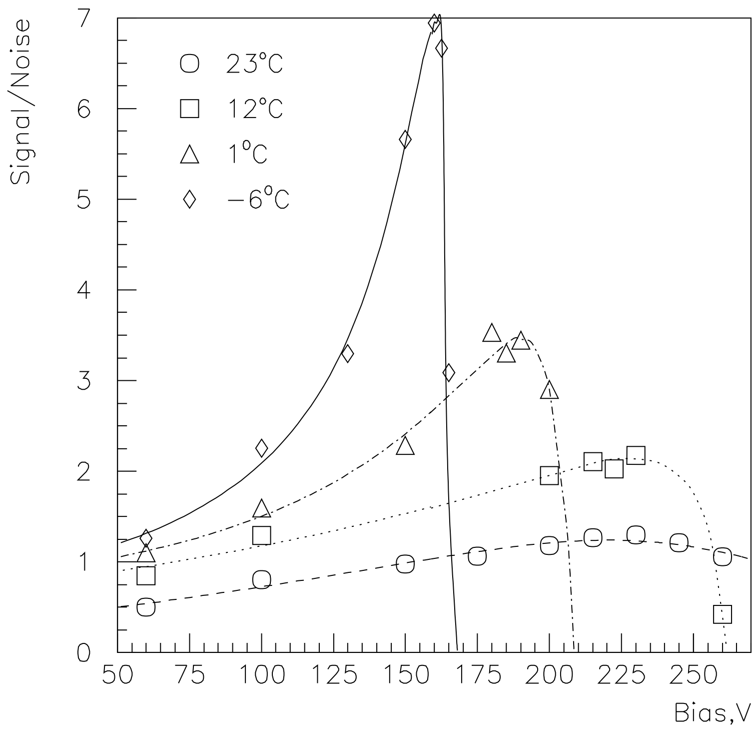


Figure 7: The Signal/Noise ratio as a function of the applied bias voltage at different temperatures. LED intensity ≈ 35 photons.

- On fig. 7 the Signal/Noise ratio as a function of the bias voltage is plotted. The cooling of APD allow us to increase drastically the Signal/Noise ratio. The maximum of this ratio can be achieved at bias voltages near the breakdown where the signal is already large while the noise is still low. Further increase of the voltage results in abrupt increase of the noise. It's clear that even for low intensity light sources, cooled APD gives a considerable S/N ratio.

6. Measurements with muons

The response of a single scintillator tile-fibre readout to the muons has been measured using cosmic muon flux and muon beam at SPS accelerator at CERN. The cosmic muons have been accounted by two scintillator trigger counters, the scintillator tile inserted in between them. During the measurements at SPS beam, we have added to the beam counters $4 \times 4\,\mathrm{cm}^2$ scintillator placed just in front of the tile under investigation. The tests have been made with PMT and APD readouts in a wide temperature range.

We have obtained $1.5 - 2$ times higher efficiency of Bicron 99-172 fibre over Bicron 91A fibre and $1.25 - 1.5$ times over Kuraray Y11 fibre using APD readout due to the higher photodiode quantum efficiency at longer wavelengths of incoming light. The results obtained with Bicron 99-172 fibre are presented on fig. 8 and fig. 9.

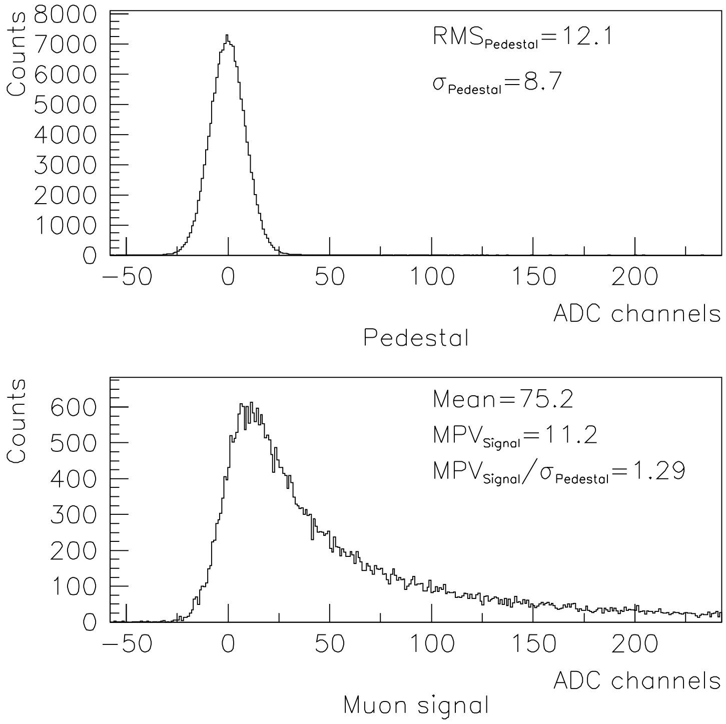


Figure 8: Muon signal from $22 \times 22 \times 0.4\,\mathrm{cm}^3$ scintillator with 2 coils of Bicron 99-172 fiber (-8^o C, 155 V bias voltage, 160 ns gate).

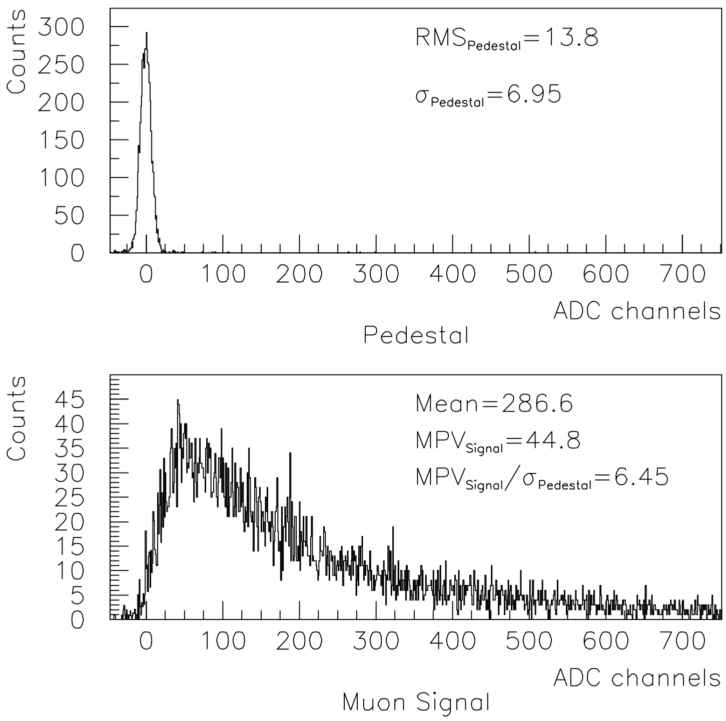


Figure 9: Muon signal from $4 \times 4 \times 1$ cm^3 scintillator with 10 coils of Bicron 99-172 fiber (-9^oC, $155V$ bias voltage, 160 ns gate).

Due to the long right-handed Landau tail in the muon signal distribution, in what follows the S/N ratio is defined as a ratio of the signal distribution maximum MPV (Most Probable Value) [9] to the σ of pedestal. The spread of the tail is determined mainly by the low light yield from the scintillator and by the induced degradation in the signal distribution due to fluctuations in the amplification process (see Section 3). Taking into account that F rises linearly with the bias voltage applied, we have to find the operational voltage at which the S/N ratio is good enough , keeping the RMS of the signal distribution as low as possible. We have found that the compromise is reached at $U \approx 110\,V$ (see fig. 10) for the photodiode used.

We have calculated the MIP detection efficiency (the ratio of the number of events in the signal distribution above 2σ from the pedestal to the number of all events in the signal distribution) for different bias voltages (fig. 11).

The main purpose of the $LHCb$ calorimeters is to identify electrons and hadrons and to provide measurement of their energy and position. Identification of electrons and photons at the trigger level is extremely important in $LHCb$. Among the various contributions to the background in the electromagnetic calorimeter one of the main concerns is the contamination due to misidentified pions. It has been found that pion rejection using only the information given by the electromagnetic and hadron calorimeters is not sufficient, and a preshower detector is needed to provide better identification of electrons and photons. A preshower structure made of a lead and scintillator, respectively 14 mm ($2.5 \times X_0$) and 10 mm thick, was chosen. Electron passing the lead absorber initiates an electromagnetic shower, thus giving a bigger signal in the scintillator than pion. The Monte-Carlo simulation shows that the optimum pulse-height cut in the scintillator corresponds to 5 MIPs, providing a satisfactory pion rejection with an electron acceptance better than 90%. Therefore, an important issue is the ability of the scintillator tile-fibre readout to separate clearly the signals from pions and electrons. A separation ratio (the ratio of the number of the events in the signal distribution below $5 \times MPV$ to the number of all events in the signal distribution) as a function of the bias voltage is presented on fig. 12.

For bias voltage of 110 V we have satisfactory levels for the detection efficiency ($\approx 85\%$) and a separation ratio ($\approx 95\%$).

We have also performed tests with different gates (fig. 13) in order to investigate the behavior of the readout system in various readout schemes. The best result for the S/N ratio is achieved when the ADC gate is near to the full width of the signal (160 ns). At narrower gates (for example 50 ns) S/N decreases by 25%. At wider gates the signal is reduced by negative undershoot in the signal wave form while the noise increases with the gate width. For these reasons, S/N falls down rapidly at gates larger than 160 ns.

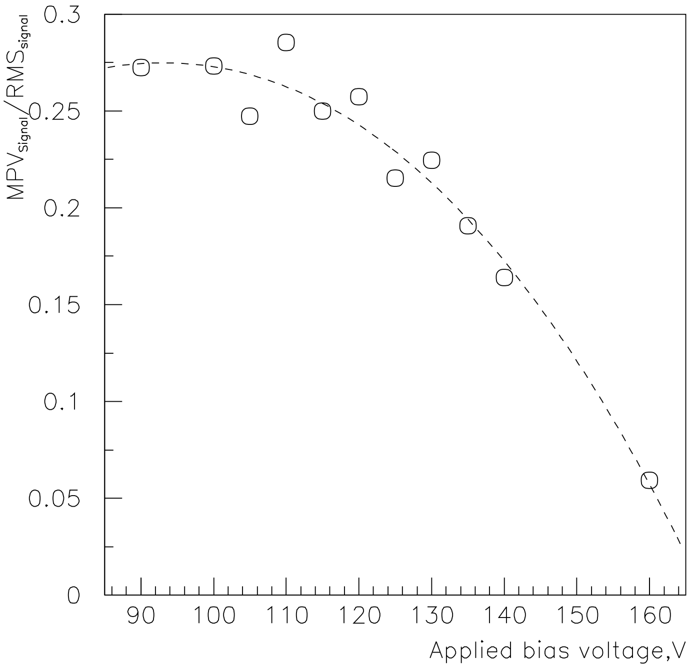


Figure 10: The most probable value of the signal divided to RMS of the signal as a function of the applied bias voltage. $4 \times 4 \times 1$ cm^3 scintillator with 10 coils of Bicron 99-172 fiber (-9^o C, 100 ns gate).

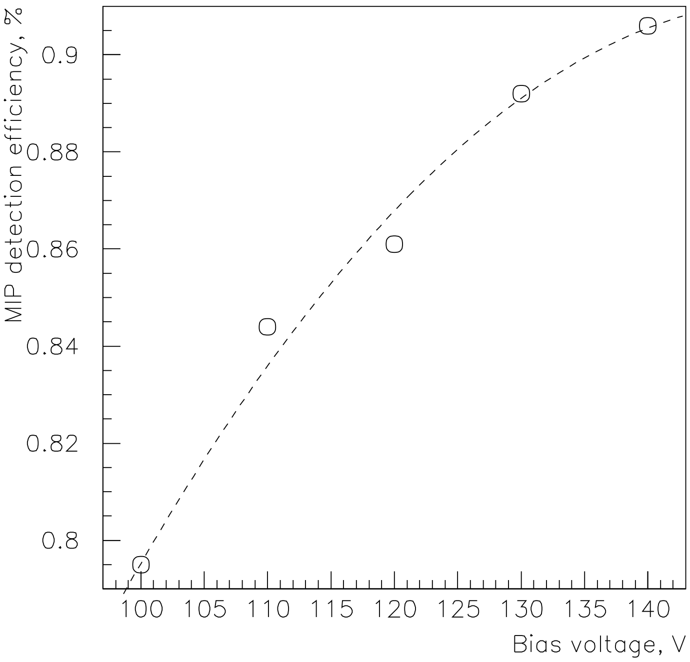


Figure 11: The MIP detection efficiency as a function of the applied bias voltage. $4 \times 4 \times 1$ cm^3 scintillator with 10 coils of Bicron 99-172 fiber (-9^o C, 100 ns gate).

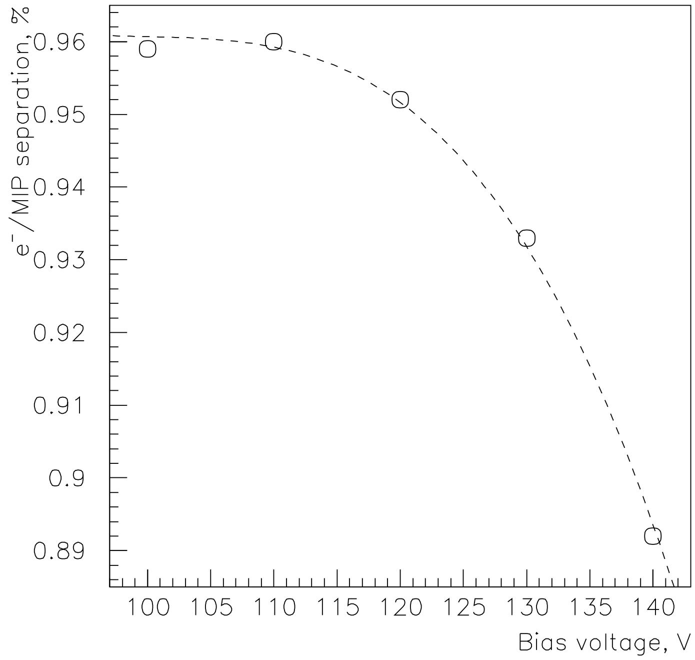


Figure 12: The e^-/MIP separation as a function of the applied bias voltage. $4\times4\times1\,\mathrm{cm}^3$ scintillator with 10 coils of Bicron 99-172 fiber (-9^o C, 100 ns gate).

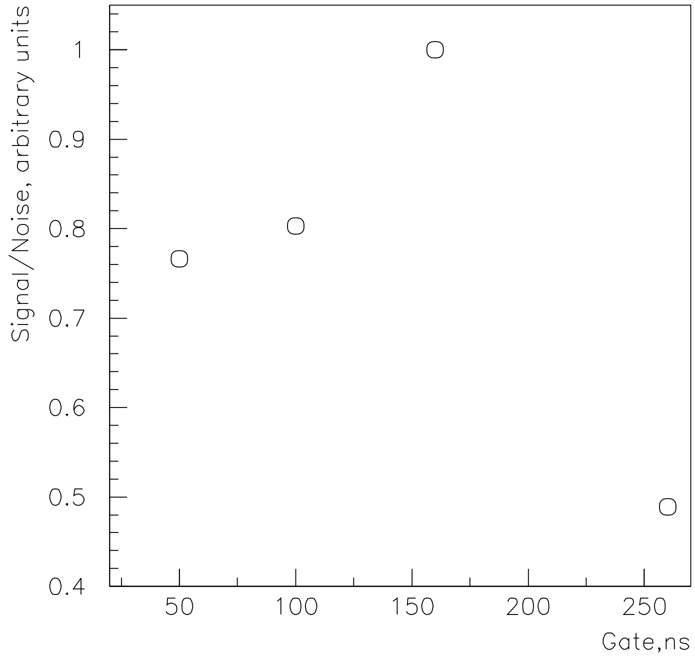


Figure 13: The Signal/Noise ratio as a function of the ADC gate. $4\times4\times1\,\mathrm{cm}^3$ scintillator with 10 coils of Bicron 99-172 fiber (-9^o C, 153 V bias voltage).

7. Conclusions

Avalanche photodiodes have been tested as a scintillator tile-fiber readout for CMS HCAL and LHCb ECAL preshower. Various types of fibres have been investigated and Bicron 99-172 has been found to be the most efficient one. A low noise charge sensitive preamplifier with $\approx 400e^-$ equivalent charge noise has been designed to gain the signal from photodiodes. For LHCb ECAL preshower scintillator a Signal/Noise ratio of 6.5 and for CMS HCAL scintillator a Signal/Noise ratio of 1.3 have been achieved by cooling the APDs down to -10^o C. A satisfactory MIP detection efficiency of $\approx$ 85% and an excellent e^-/MIP separation of $\approx$ 95% for preshower scintillator have been reached.

Acknowledgments

We would like to express our gratitude to Y. Musienko for the useful discussions and consultations and to P. Slavchev ("Inter Q" Ltd.) for developing and manufacturing the cooling device.

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