PROCEEDINGS OF SCIENCE

Selection of Silicon Photomultipliers for ILC Analogue Hadron Calorimeter Prototype

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The results of parameter measurement and selection of big sample of novel silicon photo multipliers developed in the collaboration MEPhI-PULSAR for ILC analogue hadron calorimeter prototype constructed in the frame of CALICE collaboration are presented. The multi channel test set-up is described. Detector selection criteria and their choice motivation are discussed. Comparison of photon multi pixel Geiger detectors from Russian and Japanese manufacturers is given.

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1. Introduction

Presented results have been obtained during construction of hadron calorimeter prototype for ILC in the frame of CALICE collaboration (see reference 1 for example). The physics goals at future colliders forward requirement of excellent energy resolution for such a calorimeter (~30%/√E) which may be reached using "particle flow" approach. This results in obligatory high granularity in both longitudinal and transversal directions.

The cubic meter prototype has 38 planes of 5 mm thick scintillators interleaved with 20 mm thick steel absorbers. Each of 30 first detector planes contains 100 of 3×3 cm^2 scintillator tiles in the central part. These are surrounded by 96 of 6×6 cm^2 detectors. There are 20 of 12×12 cm^2 scintillators at the plane periphery. Rear 8 planes of the prototype comprise 141 detectors. All scintillator tiles are read out with help of wave length shifting (WLS) fibers. The total number of photo-detectors needed for the prototype, the tail catcher employing scintillator strips with WLS fibers and spare detectors exceeds 9000.

We have chosen for prototype construction novel solid state photo-detectors – silicon photomultipliers (SiPM). This is a matrix of tiny photo diodes –"pixels" working in Geiger mode and connected to a common bus. Because of big amount of pixels the output signal is equal to the sum of standard signals of individual pixels and is proportional to the number of photons impinging the SiPM area.

A small 99 channel calorimeter with a novel SiPM readout was constructed by ITEP and MEPhI CALICE groups and tested at the DESY positron beam in 1-6 GeV/c momentum range[2]. This test showed that SiPM is an adequate photo-detector for the calorimetry. The measured response linearity, energy resolution, longitudinal and transversal shower distributions are in good agreement with Monte Carlo calculations.

Like ordinary vacuum phototubes SiPMs have high gain (~10^6) and photon detection efficiency (10-20%). They are not sensitive to magnetic field, operational at low voltage (30-80 V), match to WLS fiber readout by size and spectral sensitivity, have very small size (~10 mm^3).

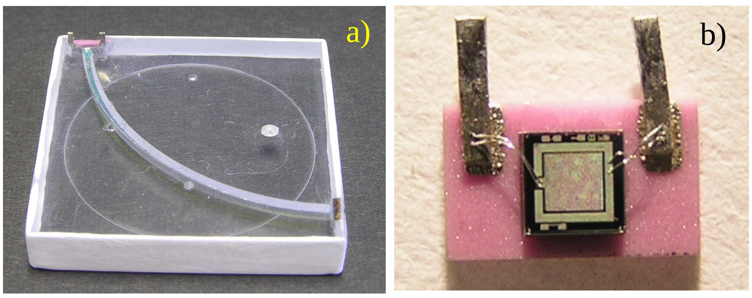

Fig.1 a) – 3x3 cm^2 tile with a SIPM, b) – SiPM picture.

Among drawbacks it is worth to notice high noise which may reach ~MHz at 1/2 p.e. level, inter-pixel optical link (cross-talk) and limited dynamic range ~1000 p.e. due to finite number of pixels.

We have used for cubic meter prototype SiPMs manufactured by MEPhI-PULSAR collaboration[3]. These devices have 34×34 pixel matrix at 1.12 mm^2 area. Thanks to extremely small size of a photo-detector we have it incorporated in a scintillator without noticeable loss of efficiency (Fig 1).

2. The flow chart of photo-detector selection

As SiPM is a non linear device it is very convenient to have all photo-detectors equalized by response expressed in pixels. We have chosen value for response of 3×3 cm^2 tile to MIP to be equal 15 pixels.

This choice is a compromise between requirements to have high (>95%) efficiency to MIP at 1/2 MIP threshold and from other hand requirement to have dynamic range as wide as possible.

Then following steps have been performed:

1) Tune bias voltage for each SiPM to have response of 15 pixels
2) At chosen voltage measure main SiPM parameters: gain (G), cross-talk (xt), noise at 1/2 p.e. level (F_0), current (I) and its stability (RMS_I), noise at the 1/2 MIP level ($F_{1/2MIP}$), response curve in the ~0.3 - 200 MIP range.
3) Apply selection criteria: $G > 4\times10^5$ in 140 ns gate, $F_0 < 3$ MHz, $I < 2$ μA, $RMS_I < 20$ nA, $F_{1/2MIP} < 3$ kHz, xt < 0.35, response to light ~200 MIPs > 900 pixels.

Minimal gain is chosen from requirement to have individual pixel peaks separated and eliminate noise of FE electronics above 1/2 MIP threshold. 3 kHz limit at $F_{1/2MIP}$ is caused by the requirement to have number of noise hits in an event of order of 1 per 8000 channels. Limits at xt and F_0 correspond to limits at $F_{1/2MIP}$, requirements of high MIP efficiency and wide dynamic range.

4) Keep SiPMs at elevated (+3.5 V) voltage during at least 40 hours. This allows detecting those devices which due to technological defects have discharge between the common bus and pixel area.
5) Repeat measurement of SiPM parameters to confirm that SiPM parameters have not been changed.

3. Set up for SiPM parameter measurement

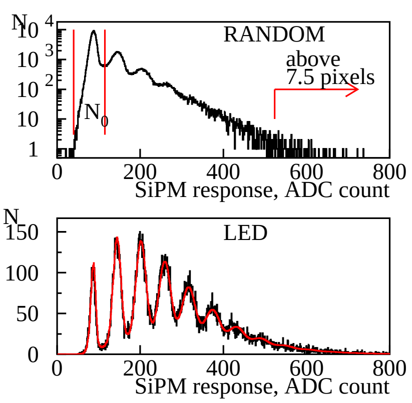

Fig.2 Response of a SiPM to random trigger and LED light.

Set up is realized in CAMAC standard. It includes: 16 channel computer driven power supply to feed SiPM's with 5 mV resolution, 110 V maximal output voltage and 100 μA maximal output current; 16 channel computer read-out digital voltmeter to monitor SiPM bias voltage, SiPM current and temperature during test. Voltmeter measurement accuracy is 5 mV, 5 nA and 0.2^o for voltage, current and temperature, correspondingly. Besides set up includes: two units of 16 channel 12 bit ADC 0.25 pC/count sensitivity, PC driven generator to produce LED and random triggers and ignite LED, PMT to monitor LED light. Measurements of SiPM response to low light have been done with use of additional amplifier with gain ~100. 15 SiPMs can be tested simultaneously. Trigger rate was equal to 2 kHz.

Software package was developed to make easy interface between user and hardware, to perform measurements and to save results in database.

During measurements response of a SiPM to random trigger and to LED light have been taken (see Fig.2). F_0 and $F_{1/2MIP}$ are extracted from random trigger spectrum: F_0=-log(N_0/N_{tot}); $F_{1/2MIP}$ = $N_{>1/2MIP}$/N_{tot}/T_{gate}. Here N_0, N_{tot}, $N_{>1/2MIP}$ are number of entries in pedestal peak region, total number of entries, number of entries above 1/2 MIP threshold, correspondingly. T_{gate} denotes gate width. Fit of LED spectrum with Poisson distribution distorted by cross-talk gives values of G, xt, N_{pe}.(see Appendix in [4]).

4. Results of SiPM parameter measurements

Distributions over parameters of more than 10000 tested SiPMs are shown at Fig.3. Red arrows show the applied selection criteria. Fraction of rejected devices is due to bad: gain – 2.8%, noise at 1/2 pixel – 5.5%, noise at 1/2 MIP – 22.6%, cross-talk – 3.5%, current – 0.5%, current RMS – 1.4%. Yield of good SiPMs is more than 70%.

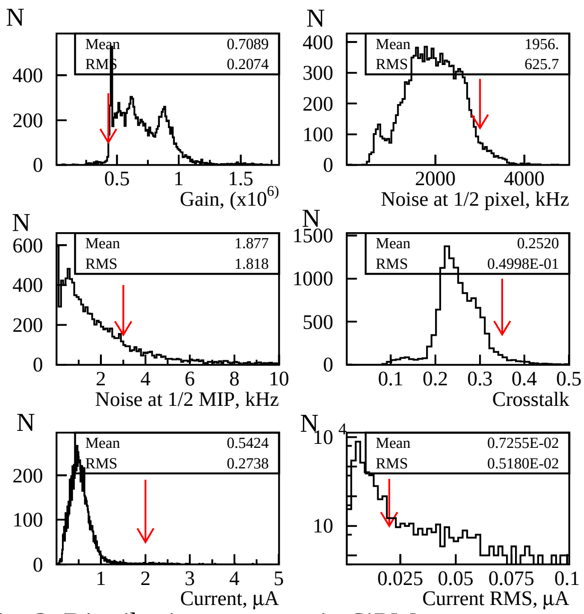

Fig. 3. Distributions over main SiPM parameters.

The accuracy of measurements was determined from multiple tests of the same SiPMs in the same test bench channels. Accuracy of bias voltage is 0.1%, for noise frequency at 1/2 MIP level we have got 10% accuracy, and other parameters have measurement accuracy 2-3%.

From measurements of parameters at various bias voltages it is possible to derive value of parameter variation at V_{bias} variation. We have obtained mean values of relative variation for gain - 2.9%, number of pixel per MIP – 3.7%, response – 6.4%, photon detection efficiency (PDE) – 2.2%, noise frequency at 1/2 p.e. – 3.5%, cross-talk – 4.7% per 100 mV bias voltage variation.

Measurements of SiPM parameters and determination of operational bias voltage have been repeated many times (~100) during almost 2 years with set of 15 SiPM's. Analysis of these data shows the stability of the set up and gives opportunity to study the temperature dependence of main SiPM parameters as temperature was not stable during measurements. The temperature dependence of breakdown voltage on temperature derived from these measurements is 57 mV/K. The accuracy of operational bias voltage determination at variable temperature is

52 mV what is comparable with accuracy of single measurement. Dependence of noise frequency at 1/2 p.e. level may be well described by $F_0(T)=F_0(T_0)\times\exp((T-T_0)/T_t)$, where $T_1=12.9\pm0.2$ K. Noise frequency at 1/2 MIP level is described by the same expression with temperature factor $T_2=6.1\pm0.2$ K.

5. Comparison of parameters of multi pixel Geiger mode photo-detectors

New photo-detectors manufactured by Hamamatsu Photonics K.K. recently became available. We have done the comparative test of such MPPCs with Russian MRS APD from CPTA enterprise with ~550 pixels/mm^2 and SiPMs from MEPhI-PULSAR collaboration (Fig. 4).

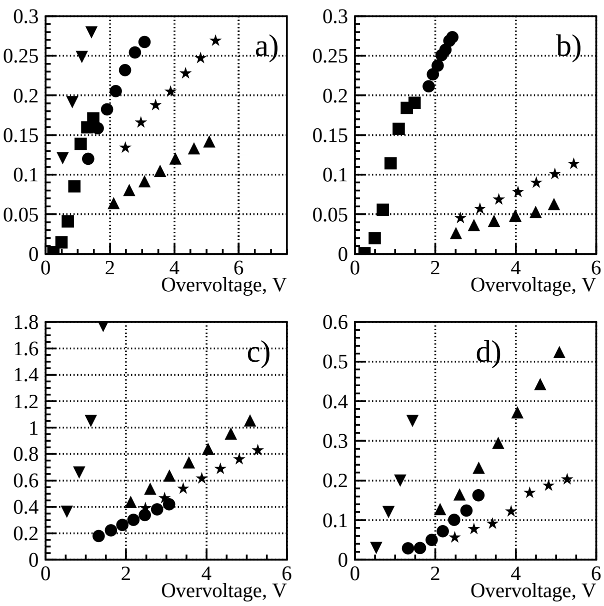

Fig. 4. Dependence of parameters of various multi pixel Geiger photo-detectors on overvoltage: a) – green light PDE , b) – blue light PDE, c) – gain (x10^6), d) –cross -talk. ● – 1600 pixel MPPC, ▼– 400 pixel MPPC, ▲ – SiPM, ■ – MRS APD 1 mm^2, * – MRS APD 4 mm^2.

Designed to work in blue region of spectrum MPPCs have 2-3 times more PDE in blue light. MRS APD with 2x2mm^2 area has PDE close to MPPC. At green light PDE of MPPC and MRS APD are close to each other (15-25%). Gain of 1600 pixel MPPC is more than twice less than gain of SiPM and MRS APD. 1600 pixel MPPC and MRS APD have rather low cross-talk – less than 0.2. 400 pixel MPPC has larger efficiency and gain but larger Xtalk. Comparison of mode photo-detectors: noise at level 1/2 pixel shows that noise frequency of single samples of 1600 pixel and 400 pixel MPPCs is smaller by at least one order of magnitude.

6. Radiation hardness of Geiger mode multi pixel photon detectors

We have tested various types of detectors: Hamamatsu MPPCs, MRS APDs and SiPMs. Gammas from ^{60}Co with energy up to 1.33 MeV have been used. The dose rate was 330 kRad/hour. The maximal dose was 800 kRad.

All devices except one are operational after maximal dose but with increased dark current and deteriorated single photoelectron resolution. For most of tested devices the increase of current is seen to be proportional to accumulated dose ΔI ~(1-3)μA / 500 kRad. However 1600 pixel MPPC shows several times worse proportionality: current increased up to 14 μA after the first 200 kRad and up to 60 μA after the second 200 kRad.

1600 pixel MPPC shows big annealing effect after doses of 200 kRad and 400 kRad. This is illustrated at Fig.5. Irradiations were done at 0 and 200 hours. After first 200 kRad current felt down to level 1 μA after 100 hours, and after second irradiation the minimal current decreased to 5 μA level after 300 hours. Each point after irradiation at Fig.5 was measured after several hours after bias voltage was on. During this time the current was not stable. This is shown at Fig. 6 where current behavior is plotted versus time after voltage switching on.

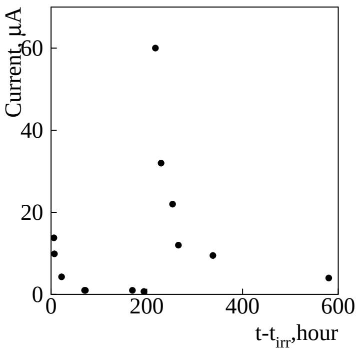

Fig. 5. Dependence of current of MPPC 1600 pixel on time after irradiation. Doses of 200 kRad were applied at t=0 and t=200.

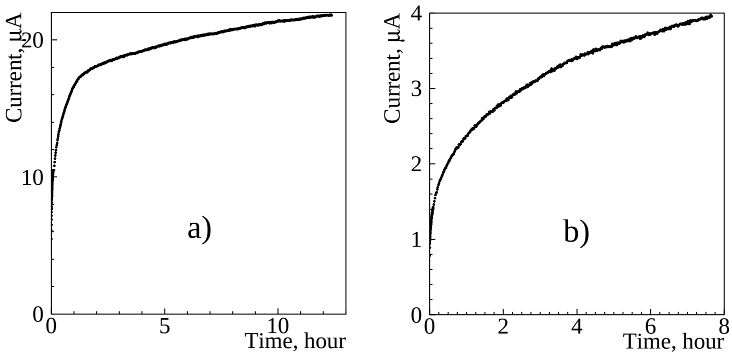

Fig. 6. Current of 1600 pixel MPPC versus time for time points of Fig.5: a) – 260 hours, b) – 580 hours.

Conclusions

We have tested and made selection of more than 9000 SiPMs for prototypes of hadron calorimeter and tail catcher for future linear collider experiments. The computerized LED test bench for SiPM test and selection has been designed, constructed and used for measurements at ITEP. Parameters of selected SiPMs meet requirements from the physical performance. Variation of SiPM parameters at variable bias voltage and temperature have been measured. Comparison of various Geiger mode multi pixel photo-detectors has been done. Radiation hardness of photo-detectors from various manufacturers has been studied. This work has been supported by ISTC grant # 3090.

References

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