PHOTODIODE READOUT OF BGO AND NaI(Tl)*

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(Presented by Helmut Vogel)

SUMMARY

We present first results using a photodiode readout for BGO and NaI(Tl) crystals. The measurements indicate that photodiodes might replace photomultiplier tubes in electromagnetic calorimetry. Using commercial photodiodes, a noise equivalent r.m.s. error of 1-2 MeV has been observed using cosmic ray measurements at T = 20° C. Preliminary tests at T = -25° C yield significantly lower values. Limitations and possible future improvements are discussed.

INTRODUCTION

In high energy physics experiments at e^+e^- colliders, compact high resolution electromagnetic (e.m.) calorimeters can be built with Bismuth Germanate (BGO), a novel scintillator of short radiation length X_o = 1.12 cm (NaI(Tl): 2.6 cm). The energy resolution should be equal or superior to that of NaI(Tl). By now, crystals of BGO up to 18 X_o long are grown routinely with good uniformity. Further details on BGO are discussed in Ref. 1. The high light output of BGO suggests to replace the standard photomultiplier (PM) readout by a photodiode (PD) readout. Recently large area photodiodes of acceptable quality became available commercially. Replacing PM readout of BGO and NaI by PD readout is very appealing because of

(i) The high stability (short and long term) of PDs,
(ii) Their large dynamic range and linearity,
(iii) Simple routine monitoring and calibration, and
(iv) The possibility of operating the calorimeter in magnetic fields.

A comparison of the features of PDs and PMs is given in Table 1. Additionally some optical characteristics versus wavelength are shown in Fig. 1. The slow signal speed of PDs (<1 MHz) does not limit their use at large e^+e^- colliders. The basic problem using PD readout is how to minimize the noise equivalent r.m.s. error (NES), defined by

$$\text{NES (MeV)} = \frac{\text{r.m.s. noise (PE)}}{\text{signal (PE/MeV)}}$$

(where PE = no. of photoelectrons).

Table 1. Comparison of properties of PDs versus PMs

Item	PM	Photodiode
<quantum efficiency>[1]	12%	60%
int. amplification	yes	no
stabilized HT	yes	not necessary
typical dynamical range	10^4	10^8
short term stability	1 (.3) %	<.01 %
long term stability	1 (.3) %	<.1 %
temperature coeff.	<.2 % /°C	<.2 % /°C
rise time	5-50 nsec	>100 nsec (area dep.)
magn. shield	complicated, impossible for high fields	unnecessary
noise immunity	high	low
price[2]	>USD 50	USD ~10
price of amplifier[2]	USD 5	USD 15

[1] integrated from 450-550 nm wavelength

[2] estimated for very large quantities

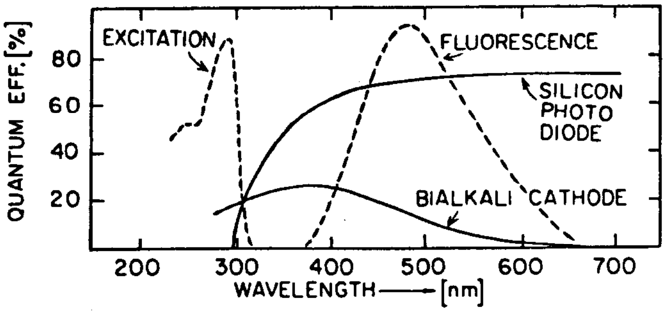

Fig. 1 Some spectral characteristics of BGO, PMs, and PDs[2,3]

Under unoptimized conditions, PDs yield signal = $\mathcal{O}$(500 PE/MeV) and noise = $\mathcal{O}$ (5000 PE), thus NES = $\mathcal{O}$ (10 MeV). Aiming for energy resolution of $\mathcal{O}$ (1%) at all energies >100 MeV, NES figures of $\mathcal{O}$ (.3 MeV) have to be achieved.

TESTS WITH BGO

The tests were performed with commercial PDs of the type Hamamatsu S 1337 BR 1010 (high resistivity silicon, area = 1 cm^2 per diode, plastic encapsulation). Figure 2 shows the basic circuit for the photodiode readout. For low noise performance the diode is reverse biased. The signal is amplified by a high quality charge sensitive preamplifier (Canberra 2003 BT) which in turn is connected to a second amplifier with a pulse shaping network for best signal/noise filtering (Ortec 472, shaping time constants 2 μs or 6 μs). The final unipolar output was fed into a voltage sensitive MCA.

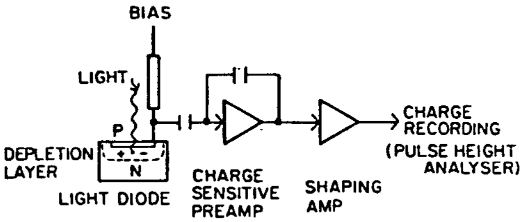

Fig. 2 Principal setup for PD readout

Three diodes were coupled to a BGO crystal with optical grease. The crystal was wrapped in white paper and made light tight. The crystal had a size of 150 × 44 × 20 mm and was viewed through its smallest face, the area of which ($7(X_o)^2$) is typical for calorimetry application. The external diode case dimensions were 15 × 15 mm^2, resulting in an area matching factor of 0.34. An increase of 20% of the signal was observed after painting the areas between diodes with white paint. The diodes were reverse biased up to 40 volts. Increasing the voltage decreases the diode capacitance C_d($C \sim 1/\mathrm{sqrt}(U)$ until fully depleted) but increases the leakage current I_d. For optimization the PDs had to be preselected. About 50% of the PDs (normally rated for max. U_b of 5 V) had sufficiently high breakdown voltage and acceptably low I_d to balance the noise contribution of the diode capacitance C_d at U_b = 40 V. Cosmic ray muons were used as test particles. They deposit by ionization about 9 MeV per traversed cm of BGO. The passage of a cosmic muon was sensed by two scintillation counters mounted above and below the BGO crystal. The fast coincidence signal was used to generate a gate signal for the pulse height analyzer. Additionally a precision pulser was connected to the input of the charge sensitive preamp through a 1 pF capacitance. The pulser was used for charge calibration, linearity tests and noise evaluation. Figure 3 shows the block diagram of the test setup.

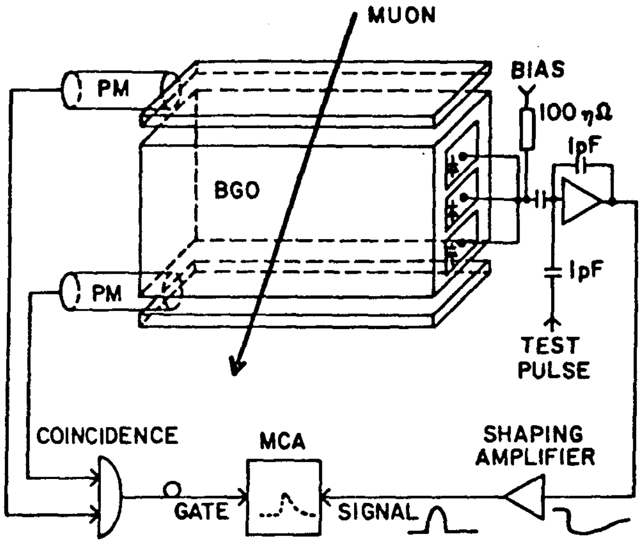

Fig. 3 Setup for PD readout used in the test

Figure 4 shows the observed pulse height distribution together with the distributions of both pedestal and calibration pulses. The width of the energy loss spectrum was measured to be 33%. Correcting for the angular acceptance of our triggering setup, the width extrapolated to perpendicular passage becomes 22 ± 2% which is consistent with results obtained in a test beam of 140 GeV pions using PM readout. The results together with that of a crystal of different dimensions are summarized in Table 2.

Remarks

(i) Note the improvement of the noise figure with increasing shaping time constant.

(ii) The numbers given for low temperatures are still preliminary since tests are currently under progress.

TESTS WITH NaI(Tl)

Due to the substantially higher light output of NaI(Tl) per MeV energy deposit w.r.t. BGO, the PD readout of NaI(Tl) yields satisfactory results even under non-optimized conditions. At T = +25° C we measured NaI(Tl) pulse height spectra for

(i) A crystal of size 280 × 40 × 40 mm^3. viewed by three PDs through a plexiglass light guide with a very low area matching factor of 0.16 using cosmic rays,

(ii) A cylindrical crystal of size Ø 38 × 38 mm, viewed by four PDs, the space between the PDs being treated with diffuse reflector. In this case, we were able to take spectra of Co^{60} and Cs^{137} sources in a self triggering mode (see Fig. 5). The results are shown in Table 2 also.

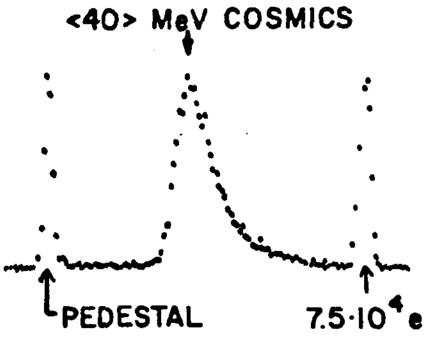

Fig. 4 Observed energy loss spectrum of cosmic muons in 44 mm of BGO, together with pedestal and calibration pulse distribution

Table 2. Summary of test results using PD readout[5]

Crystal, dimensions (mm)	Number of diodes	T (°C)	τ shaping (μsec)	AMF*	Number PE/MeV	NES (MeV)
BGO						
150 × 44 × 20^1	3	+20	2	0.34**	910	1.80
150 × 44 × 20^1	3	+20	6	0.34**	850	1.12
200 × 30 × 30^1	4	+20	6	0.44	860	1.15
200 × 30 × 30^1	4	-12	6	0.44	1430	0.60
200 × 30 × 30^1	4	-25	6	0.44	1680	0.54
NaI(Tl)						
280 × 40 × 40^2	3	+20	2	0.16	1200	1.10
NaI(Tl)						
38 × 38 Ø^3	4	+20	6	0.35**	7000	0.16

^1U_b = 39 V, ^2U_b = 30 V, ^3U_b = 25 V

*area matching factor, **white reflector paint between diodes

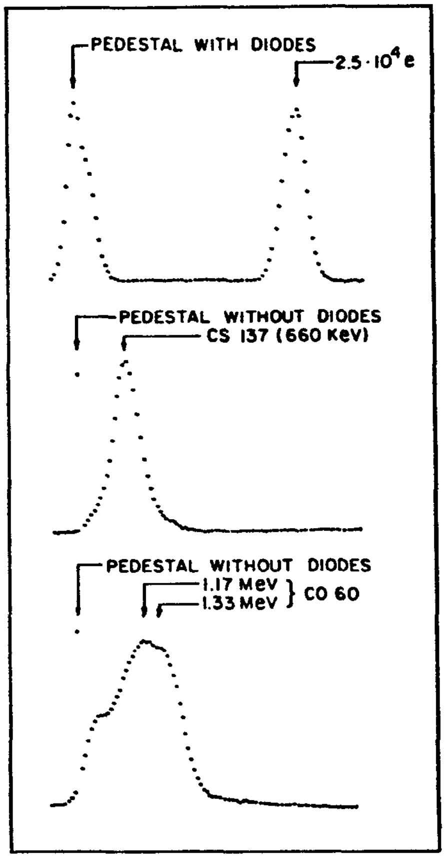

Fig. 5 Spectra obtained with a small volume crystal of NaI(Tl):
(a) pedestal and calibration pulse distribution
(b) spectrum of Cs(137) source
(c) spectrum of Co(60) source

FURTHER IMPROVEMENTS AND TRADEOFFS

The aim of this study was to establish the feasibility of the photodiode readout with acceptable low noise. The main contribution to the noise comes from

(i) shot noise of the preamplifier input FET multiplied by the diode and input parallel capacitance.
(ii) shot noise of the diode leakage current for large bias voltages.
(iii) noise due to leakage current of the electrical connections and diode p - n edge effects.

A typical example of the noise figure versus diode capacitance and dark current as a function of bias is shown in Fig. 6.

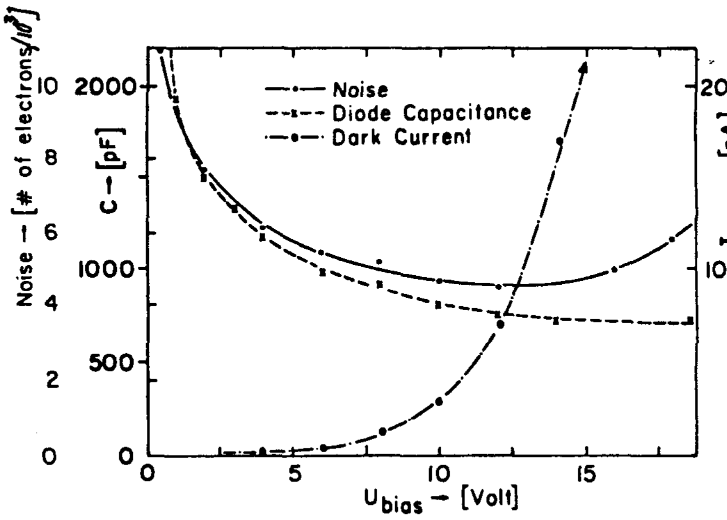

Fig. 6 NES, diode leakage current, and capacitance versus reverse bias voltage for a set of 3 parallel connected diodes of moderate quality

Modern charge sensitive preamplifiers have intrinsic typical noise values of equivalent of 300-1000 PE and slopes of 5-10 PE per pF of detector capacitance. For best NES values a low diode capacitance is always necessary. The contribution of shot noise of the diode leakage current becomes only significant above ~200 nA. Diode p - n edge effects or connector leakage currents can sometimes be quite unpleasant and require the selection of adequate materials or diodes.

Compared with the described tests further improvements of the noise figure are possible:

(i) Better area matching together with preamplifiers with low noise for large diode capacitances.
(ii) Improved optical coupling with high refractive index materials, antireflex coating or BGO surface treatment with diffuse reflectors.
(iii) Use of photodiodes made of high resistivity Silicon and high bias voltage, i.e., low diode capacitance.
(iv) Cooling of the BGO will result in a substantial signal increase (in first order the reduction of 40° will result in an increase of a factor 2).

The reduction of the diode capacitance can only be achieved by increasing their depletion layer. This might have an unpleasant side effect. The photodiodes act as nuclear counters and traversing charged particles will create a signal of about 100 charged pairs per micron depletion layer (minimum ionizing particles). This effect is well demonstrated in a test exposing the photodiodes to a β source. We observe a signal of ~10000 PE corresponding to an equivalent energy loss of ~12 MeV in the BGO. For critical applications the diodes have to be placed into areas of low charged particle flux.

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   M. Cavalli-Sforza, these proceedings.
2. M. J. Weber, R. R. Monchamp, Journal Applied Physics 44 (1973) 5495.
3. Hamamatsu catalog: Photomultiplier Tubes 1980.
   Hamamatsu catalog: Silicon photocells 1981.
4. DOW CORNING optical coupling grease Q2-3067, $n = 1.4648$ (λ = 589 nm)
5. Errors on the number of photoelectrons are typically 10%. Error numbers are normally omitted as the quoted numbers are only meaningful for the above described test setup and will change significantly for different arrangements.