CERN-PPE/92-159
31 August 1992

TEST RESULTS OF THE FIRST PROXIMITY
FOCUSED HYBRID PHOTODIODE DETECTOR
PROTOTYPES

S. Basa, J-C. Clemens, M. Commerçon, D. Sauvage, S. Tisserant
*Centre de Physique des Particules (CPPM), Faculté des Sciences de Luminy,
IN2P3-CNRS, 13288 Marseille, France*

J-M. Gaillard
*Laboratoire de L'Accélérateur Linéaire (LAL), Université de Paris-Sud,
IN2P3-CNRS, 94405 Orsay Cedex, France*

ABSTRACT

A new type of light detector, the Proximity Focused Hybrid Photodiode Detector, has been constructed and its properties have been studied. The main features of the new device are a gain of up to a few thousand varying linearly with the applied high voltage, a large dynamic range, a low sensitivity to magnetic field, a power consumption close to zero and a multipixel capability.

(Submitted to Nuclear Instruments Methods)

1 - INTRODUCTION

The Proximity Focused Hybrid Photodiode Detector (PFHPD), whose principle is shown schematically on Fig. 1a, is a new type of light detector comprising two active components :

- a glass or fiber-optics input window on which a semi-transparent photocathode is deposited just as in a conventional photomultiplier (PMT),
- an output disk equipped with a reverse biased silicon detector (anode), placed in close proximity ($\cong 1.5$ mm) to the photocathode, which acts as an electron detector.

Those components are vacuum sealed to both ends of a ceramic cylinder. A large electrical field, HV, with a strength of about 10 kV, is applied between the two electrodes. The photoelectrons produced in the photocathode are accelerated to the full voltage before entering the silicon detector, where they produce 1 electron-hole pair per 3.62 eV. There is a thin passivation dead-layer on the silicon which corresponds to a mean energy loss HF without pair creation. The electron gain is therefore $(HV-HF) / 3.62$ and can reach a few thousands.

The power consumption of the device at the present state is dominated by the silicon diode reverse current. As an example, for a reverse current of 10 nA and 100 V bias voltage the power consumption is only 1 μ W.

The idea to replace the conventional dynode chain of a photomultiplier tube by a silicon detector is not very new ; several important developments were done on that subject starting in the 60's [1]. However they do not seem to have evolved beyond the prototype stage due to the quality of the diodes available at that time. Hybrid phototube prototypes were also built in Astronomy for high precision photometry. An article by J.G. Cuby et al. [2], which presents the results of recent prototype tests, contains references to earlier work on that subject.

For Particle Physics, the hybrid photomultiplier idea was revived by R. DeSalvo [3]. A few hybrid photomultipliers with electrostatic focusing of the electrons made by the DEP company* were studied in detail [3]. Another hybrid photomultiplier, also electrostatically focused, which was built by ITT for Johansen and Johnson [4] is shown on Fig. 1b. Electrostatic focusing offers the advantage over proximity focusing that the area of the silicon detector is reduced relative to that of the photocathode for a better signal/noise ratio.

* Delft Electronische Producten, Postbus 60, 9300 AB Roden (Dr) Holland.

However, due to the low electrical gradient and the non-parallel electron trajectories in such devices, their performance is very adversely affected by the presence of a magnetic field.

The proposal by the RD1 collaboration at CERN to apply the proximity focusing technique to the construction of hybrid photomultipliers largely overcomes the magnetic field sensitivity problem. Due to the much larger voltage gradient, such devices are expected to be about two orders of magnitude less sensitive to magnetic field than the electrostatic ones. This article reports the test results of the first two hybrid phototube prototypes using the proximity focusing technique built by the DEP company for the RD1 collaboration.

2 - THE PROTOTYPES AND THE MEASUREMENT SET UP

The construction scheme of the two prototypes made for the RD1 collaboration is shown on Fig. 2a. They differ only by the sizes of the silicon detectors with diameters of 6 mm (area 25 mm²), and 8 mm (50 mm²), respectively. The choice of the dimensions of the silicon was dictated by the immediate availability from the firm Canberra^{**}. It is in no way a technical limitation of the device. The photocathode diameter is 18 mm.

The two silicon diodes are made with high resistivity 300 micron thick silicon in the E-type configuration in which the P⁺ implant faces the incoming electrons. An important parameter of a silicon detector is the reverse current which limits the signal to noise ratio. For the bare silicon detectors as provided by Canberra, the reverse current were around 1 nA. However, during the processing at DEP, the reverse current increased to reach the 1 μ A level. According to DEP that increase appears to occur during the baking of the tube and it will be kept under control for the next prototype generation.

A fast and powerful photon source is needed to explore the tube performance over the 10⁵ dynamic range required for LHC calorimetry application, without altering the expected fast response of the prototypes. A 10 mW Philips GaAs laser, pulsed as in the case of a conventional LED by an avalanche transistor, was chosen. With this type of light source light pulses of up to 10⁸ photons within 1 ns are generated over a 4 mm diameter beam. The wavelength of such a laser, 790 nm, is not well matched to the S20 photocathode spectral sensitivity. However the problem is compensated by the large number

^{**} Canberra Semiconductor NV, Lammerdries 25 B-2250 Olen, Belgium.

of photons available. Another difficulty, also present with conventional LED pulsing, is the signal line pick-up. Despite the fact that such an effect forbids the use of a conventional ADC, the difficulty can be overcome by using a fast digital oscilloscope. As that noise is reproducible, synchronous with the signal, and independent of the high voltage applied to the tube, it was recorded with the tube gain set to zero and then subtracted from the total signal (Figs. 3a and 3b). Such a method is simple and remains accurate except in situations where the noise level becomes very large with respect to the signal. Most of the measurements were done inside a black-box using direct laser beam illumination. Due to space limitations for the tests performed in a magnetic field the light was fed to the photocathode using a fibre optic guide.

Since there were no available amplifiers covering the complete dynamic range, the measurements were done in two different ways. For large signals the diode output was fed directly into the digital scope - 50 Ω DC coupled - through a coaxial cable. For small signals, an off the shelf charge amplifier delivering about 550 mV/pC was used, followed by a 100 ns shaper. In the first case, Fig. 3b, both the amplitude and the total charge of the signal were recorded. In the second case, only the output amplitude of the signal was measured.

Each measurement was the average of 50 consecutive pulses, each sampled by the scope at a rate of 1 point/500 ps using its interleaved sampling capacity. The overall accuracy of the method - averaging, noise subtraction and integration - is difficult to estimate with statistical methods. By doing the distribution of 50 measurements, evenly distributed over 1 hour, as in a short term stability test, a relative rms of 1.8% of the output charge was obtained. When correcting for the effects of other instability sources, such as the fluctuations of the laser light pulses, by using another detector as a reference, a rms of 1.4% was obtained.

3 - PERFORMANCE OF THE PROTOTYPES

3 - 1 - The signal characteristics

A simplified model of the silicon detector coupled directly to a scope is shown on Fig. 2b. During the time t_c that the electrons drift across its 300 μm thickness, the silicon diode acts as a current source of constant value in parallel with its own capacitance C_d and

with the input capacitance C_p (30 pF) of the scope. As only the E-type detectors were used, and since the e/h pairs were created close to the surface of the detector (as the range of 10 kV electrons in silicon is about 1.2 μm) the contribution of the holes to the signal was completely negligible.

The voltage signal was expected to reach a maximum at t_c and then to decrease exponentially with a $R(C_d + C_p)$ time constant. The capacitances C_d of the two detectors were 20 pF and 50 pF for tubes 1 and 2, respectively. The detectors were operated well beyond complete depletion and so an electron velocity of 66 $\mu\text{m}/\text{ns}$ was assumed. The expected rise time of the signal was therefore $t_c = 4.5$ ns and the fall time constants, $RC = 2.5$ ns and 4 ns for the two tubes, respectively.

The maximum amplitude of the signal, $V_{\text{max}} = RQ [1 - \exp(-t_c/RC)] / t_c$ depends not only on Q , the total generated charge, but also on R , C and t_c . However the integral $\int V = RQ$ depends only on Q and on the scope input impedance R . The digital integration of the voltage signal gives therefore an accurate estimate of Q .

3 - 2 - Gain linearity and dynamic range

The dependance of the output charge integrated over 25 ns on the applied high voltage is shown on Figs. 4a and 4b for the prototypes 1 and 2, respectively. The linearity of the gain between 6 and 10 kV is excellent ; the deviations of the data points to a straight line fit are less than 1%. The curvature observed below 6 kV is due to the electron straggling in the silicon passivation layer, corresponding to an average energy loss HF. From these measurements an approximate estimate of the absolute gain may be obtained from : $G = (HV - HF) / 3.62$. The values of HF as measured from the data are 3650 V and 3330 V for prototypes 1 and 2, respectively. The gain is about 1800 for both tubes at a 10 kV operating voltage.

The dynamic range of tube 1 was measured at 10 kV with the bias set at 130 volts on the silicon. The laser beam with a fixed intensity and a set of calibrated filters were used to cover the measured output charge range from 66 fC to 560 pC, with a 25 ns integration time constant. A preamplifier was used between 66 fC and 2.54 pC and direct scope coupling between 1.27 pC and 560 pC. The amplifier gain was calibrated using the overlap between the output charge ranges of the two types of measurements. The expected output charge, defined as being proportional to the attenuation of the filter, was normalized

such that the ratio expected/measured be equal to unity for a charge of 20 pC. Fig. 5a is a plot of the measured versus the expected output charge.

The linearity is excellent. The ratio (measured-expected)/expected shown on Fig. 5b is consistent with zero at the 2% measurement accuracy level over the full range. To scale such a plot with the incident energy for calorimetry applications, an equivalence $1 \text{ GeV} = 500 \text{ photoelectrons}$, as measured for a RD1 fibre calorimeter prototype, was used. Thus with a gain of 1750, $1 \text{ GeV} = 0.14 \text{ pC}$ is the energy scale also shown on Fig. 5a. The output charge range used for the measurements is not limited by the device. The lower end was set by the noise pick-up level and the upper end by the laser output power.

Whereas the output charge is very linear, large deviations from linearity are observed for the output pulse amplitude for high charge level as shown on Fig. 6. That effect is due to the increase of the charge collection time in the semiconductor caused by local high charge density which screens the collecting field, the so-called "plasma effect", well known in heavy ion spectroscopy [5]. Such a phenomenon might become a serious limitation if very short shaping times were used. However, for the purpose of LHC calorimetry, the linearity is preserved with a charge integration of 25 ns over the full dynamic range, even when the total signal is concentrated in this small area (25 mm^2) silicon detector, as opposed to the 500 mm^2 detection surface which will be used in the future.

3 - 3 - Magnetic field tests

A first set of measurements were made with an axial magnetic field, parallel to the direction of the 10 kV electrical field, up to 0.7 Tesla. The set-up was the same as the previous one except that the light pulses were fed to the input window via an optical fibre and a diffusing translucent disk whose diameter was the same as that of the silicon detector. The results are shown on Fig. 7a. As expected, the output charge remains constant within the 2% measurement accuracy, a confirmation of the insensibility of such a tube to axial fields. Additional measurements up to 2 Tesla are planned.

For the transverse field orientation, measurements were made up to 0.2 Tesla. Results are shown in Fig. 7b for various values of the tube high voltage. The gain is not affected up to 0.15 Tesla. That is somewhat better than the results of a simulation which predicts a continuous slow decrease of the signal with the strength of the magnetic field as

shown on Fig. 7c. Such a difference is likely to be due to a light spot diameter slightly larger or smaller than the size of the silicon detector, which would postpone the decrease of the signal due to the curvature of the electron trajectories. The offset of a photoelectron accelerated in the tube up to 10 kV in a 0.15 Tesla transverse field is only 1 mm at the silicon detector position. Such an offset can be handled by using a slightly larger silicon detector.

3 - 4 - Lifetime tests

The ageing behaviour of tube 2, equipped with a 8 mm diameter silicon detector, was measured under illumination by a yellow LED continuous light source. The high voltage was set at 8 kV for an initial gain of about 1200 and a measured output charge of 7 mC/hour, corresponding to a charge density of about 0.15 mC/mm²/hour. The gain of the tube was measured every hour with the Ga-As laser. A reference tube was used to correct for the laser beam fluctuations. The results of the gain measurements as a function of the integrated output charge up to 600 mC are shown on Fig. 8a. The gain loss is linear with the integrated charge at a rate of 4% per 100 mC. Such a loss rate is about two orders of magnitude larger than that of the bare silicon diode obtained from an auxiliary measurement reported in appendix, an indication of a photocathode effect in the later case. Following the ageing tests, scans were made across the photocathode area with a laser pencil light beam. The distributions of the photoelectron output current of the photocathode measured throughout the x and y scans are shown on Figs. 8b and 8c. The diameter of the photocathode is about two times larger than that of the silicon. The photocathode current is smaller in the region facing the silicon than outside it. Two other scans done of different wave lengths show that the relative loss increases with the light wavelength. It is about 4 times larger for $\lambda = 800$ nm than for $\lambda = 550$ nm. Such a pattern is consistent with the photocathode layer becoming thinner because of ions emitted from the silicon : high efficiency at longer wavelength is obtained with thicker photocathodes.

The ion return flux is expected to be reduced by at least an order of magnitude by cleaning the silicon diode with an electron beam before insertion in the tube (electron scrubbing). However even under the present conditions, the lifetime of the tube would be adequate to use it as a photon detector on a scintillating fiber calorimeter for LHC. For instance, if an hybrid tube equipped with a silicon detector of 1" diameter were to be used on a calorimeter cell covering $\Delta\eta \times \Delta\phi = 0.02 \times 0.02$ radian, the expected gain loss would be only 1.2% per year at a pseudo rapidity $\eta = 2$ for an integrated luminosity $\mathcal{L} = 10^{41}$ cm⁻².

3 - 5 - Beam tests

For a first beam test, a new prototype was coupled to the read-out wavelength shifting fibres of a single (11×11) cm² module of an em calorimeter made of scintillator and lead layers [6]. The new hybrid detector prototype was equipped with a 11 mm diameter silicon detector. The output signal was amplified by a factor 100. Data were taken with electrons of various energies and with muons at the CERN SPS. The output charge distribution for 40 GeV electrons is shown on Fig. 9a and gives an energy resolution σ/E of 1.8%. The muon signal is 9 pC on average, as shown by the distribution of Fig. 9b. This corresponds to an energy loss of 300 MeV. The noise level of the whole system (silicon detector + amplifier) is low. It is equivalent to 15 MeV rms.

4 - CONCLUSIONS

The Proximity Focused Hybrid Photodiode Detector represents a very promising device for light detection on future calorimeters. The new detector has a low sensitivity to magnetic field, a large dynamic range, an excellent gain linearity and an almost zero power consumption. The first beam tests show a very good signal to noise ratio.

In the near future new hybrid tubes with larger 1" diameter silicon and improved lifetime will be constructed. A multipixel capability will also become available by segmenting the silicon detector. Already now the properties of the new device are such that it will be an attractive replacement of the traditional PMT's in many applications.

ACKNOWLEDGMENTS

The cooperation of DEP for the design and the construction of the prototypes is gratefully acknowledged. The work presented here was done within the general framework of the RD1 Collaboration. We wish to thank our RD1 colleagues for fruitful discussions.

APPENDIX

LIFETIMES OF THE SILICON DIODES

The Silicon diode ageing measurements were done using a scanning electron microscope. The 10 keV electron beam provided by the microscope was used alternatively to irradiate a small well defined area of the diode, about $(100 \times 75) \mu\text{m}^2$ and to measure the gain of the irradiated area relative to that of the non-exposed region.

For the gain measurements, the electron microscope was switched to the line scan mode with a ten times smaller magnification in order to scan unaltered silicon area on both sides of the irradiated region. The principles of both the irradiation and the gain measurement operations are shown on Fig. 10.

Two types of silicon diodes were studied the so called "E" and "T" types where the incoming electron impinges on the P^+ and N^+ implant sides respectively. For both types the depletion depth of the silicon was $300 \mu\text{m}$.

The lifetest results are shown on Fig. 11 for both types of diodes. The T type appears to be more resistant than the E type. However it is also more delicate to handle because there should not be an extra silicon thickness on the N^+ implant side. Due to their immediate availability the E type diodes were used for the construction of our prototypes. For both types of diodes the lifetime is more than ample for the use in light detectors for a LHC calorimeter. As reported in section 3.4, the lifetime of the complete tube equipped with a silicon diode is estimated to be adequate for LHC application, although it is presently about two orders of magnitude shorter than the bare diode one.

REFERENCES

- [1] P. Chevalier, Nucl. Inst. and Meth. 50 (1967) 346;
J. M. Abraham, L.G. Wolfgang and C.N. Inskeep, Adv. EEP, 22B (1966) 671;
J. Fertin et al., IEEE Transactions of Nuclear Sciences, Vol. NS 15, June 1968.
- [2] J.G. Cuby, J. Baudrand and M. Chevreton, Astron-Astrophysics 203 (1988) 203.
- [3] R. DeSalvo, CLNS 87-92, Cornell University, Ithaca (1987);
R. DeSalvo et al., Nucl. Inst. and Meth. A315 (1992) 375.
- [4] G.A. Johansen and C.B. Johnson, "Operational characteristics of an electron-bombarded silicon diode photomultiplier tube", Proceedings of the Sixth European Symposium on Semiconductor Detectors, Milano (1992).
To be published in Nucl. Inst. and Meth..
- [5] W. Seibt et al., Nucl. Inst. and Meth. 113 (1973) 317;
E.C. Finch, Nucl. Inst. and Meth. 121 (1974) 431 and 129 (1975) 617;
G.F.G. Delanay et al., Nucl. Inst. and Meth. 215 (1983) 219.
- [6] That calorimeter is of the type described by G.S. Atoyan et al., Lead-Scintillator electromagnetic calorimeter with wavelength shifting fibre readout, Preprint INR-736/91, Nov. 91. We thank S.N. Gninenko and V.V. Isakov for the loan of their calorimeter and for their participation in the test.

FIGURE CAPTIONS

- Fig. 1 a) Principle of the Proximity Focused Hybrid Photodiode Detector.
 b) The ITT Electrostatic Focused Hybrid Phototube [4].
- Fig. 2 a) The DEP Proximity Focused Hybrid Photodiode prototypes.
 b) Equivalent circuit for the detector coupled to a scope.
- Fig. 3 Signal and noise treatment.
 a) Signal and noise recording.
 b) Noise subtraction and digital integration.
- Fig. 4 Output charge versus high voltage for the two prototypes.
- Fig. 5 a) Dynamic range of the PFHPD.
 b) Deviations from linearity versus the output charge of the PFHPD.
- Fig. 6 The PFHPD pulse amplitude versus the output charge.
- Fig. 7 Tests in magnetic fields.
 a) Output charge in axial field.
 b) Measured and c) Expected effects in transverse field.
- Fig. 8 a) The PFHPD gain loss versus the integrated output charge.
 b) and c) Photocathode scannings after irradiation (600 mC integrated output charge).
- Fig. 9 The output charge distributions of the PFHPD mounted on an em calorimeter for
 a) 40 GeV electrons
 b) muons.
- Fig. 10 Principles of the irradiation and of the gain measurement of the silicon diodes
 using a scanning electron microscope.
- Fig. 11 The gain losses versus the output integrated charge for the E and T type silicon
 diodes.

Fig. 1

Fig. 2

20 ns/div

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11