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REDISCOVERING THE GAS-FILLED PHOTODIODE

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ABSTRACT

Gas-filled photodiodes have been used for decades as cheap, reliable photon detectors with moderate gains. We have investigated the possibilities and the advantages of such devices for the detection of the light flash emitted by scintillators in the calorimeters used for high-energy physics, and other applications where large photon yields are expected per detection element.

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A vast majority of modern high-energy physics experimental set-ups include large-size calorimeters, which are devices where charged particles or photons interact with successive layers of high-density materials losing part or all of their energy in an electromagnetic or hadronic shower. Various methods have been developed to sample, as often as possible, the spatial growth of the energy loss within the shower; measuring the shower growth and decay one can then compute the original energy of the particle, and in some cases its trajectory. The energy resolution obtainable is dependent, amongst other factors, on the sampling efficiency (the ratio between observed and total energy loss) and on the intrinsic noise level of the individual detection elements. When several close tracks are expected -- an increasingly probable event at high energies owing to large multiplicities and clustering -- a fine granularity of the detector within each layer is necessary; this leads easily to tens of thousands of individual sampling elements in present-day set-ups [1].

A widely used method of implementing a calorimeter consists in interleaving layers of a dense material (such as lead or iron) with plastic scintillator slabs or strips, read out by photomultiplier tubes. To reduce the number of measuring channels, various grouping methods have been adopted, merging the signals of several strips on a single tube. The green-bar wavelength-shifter method has recently greatly simplified the grouping procedure, eliminating the need for complicated light-guides; for a survey of techniques and resolution calculation see, for example, Amaldi [2]. However, while reducing the number of measurement channels, grouping obviously spoils the multiparticle resolution and tends to degrade the over-all performance of the device. The question arises whether or not one can develop some kind of large-area photon detectors cheap and thin enough to be mounted directly on each scintillator slab. At present-day accelerator energies, with the shower quickly growing in converters so as to contain several hundred charged particles, a 1 cm thick plastic scintillator delivers several thousand photoelectrons on a photon detector with 10% quantum efficiency. It has been proposed [3] to use as a detector, in close contact with one face of the

scintillator slab, a vacuum photodiode coupled with an electronic charge amplifier. The development of a large-area (100 cm^2 or so) vacuum photodiode has indeed been started. Despite its attractiveness, this kind of detector suffers, however, from two intrinsic drawbacks: first, a vacuum tube needs increasingly thicker windows for large surfaces, unless one uses bulky dome-like shapes. Moreover, the noise level of cheap-enough charge amplifiers having a $1\text{ }\mu\text{s}$ or so time constant is around 10^3 electrons, thus largely degrading the expected signal resolution at low photon yields.

It has occurred to me that a gas-filled photodiode may solve one and possibly both of the above-mentioned difficulties. This kind of detector was widely used decades ago in applications where the need for moderate gains and limited bandwidths did not demand more sophisticated devices, such as, for example, in decoding the sound track in movies. Generally having a solid internal photocathode in a coaxial geometry, and filled with argon at a pressure around 1 Torr, gaseous photodiodes have been operated safely and for an extended time without degradation of performances at gains between 10 and 20, exploiting the multiplication properties of electrons in the gas [4]. Replaced by solid-state detectors, this device has apparently been dropped from production nowadays.

The Electron Tube Division of EMI^{*)} has manufactured, at our request, a few experimental samples of gas-filled photodiodes, with a design that could be adapted to the particular needs of calorimetry. The preliminary measurements realized at CERN on such devices are described here.

The best results in terms of efficiency and gain stability have been obtained by using a gas photodiode with a flat, inverse photocathode geometry, i.e. a transparent planar window coated on the inside with a light-transmitting conducting layer overlaid with a thin micromesh to improve charge collection and constituting the anode, facing a thin metal plate coated with the photosensitive layer acting as the photocathode. The active surface of the prototype was 19 mm in

^{*)} EMI Industrial Electronics Ltd, Bury Street, Ruislip, England.

diameter, with an anode-to-cathode distance of 2 mm. Such a small distance has been chosen both in order to operate at low voltages, and to aim at the realization of flat and thin detectors; for convenience, however, at this stage, the active element has been sealed in an existing cylindrical envelope about 40 mm long. The photocathode material chosen for the test was a standard bi-alkali with a spectral response range between 300 and 650 nm. After formation of the photocathode in the usual vacuum conditions, research-grade argon was admitted through several vacuum cycles, with continuous monitoring of the radiant sensitivity; a loss of a factor of two in sensitivity was noticed after the first cycle, probably due to the intrusion of trace impurities, but the response remained constant in the successive cycles. The tube was sealed off at a pressure around 2×10^{-2} Torr, according to the manufacturer: this value seems inconsistent, however, with our observations (see below).

We have tested the d.c. characteristics of the device at CERN using as source a light-emitting diode^{*)}, operating at green wavelengths, and mounted at a few centimetres from the window. Current versus voltage characteristics were recorded using a current-integrating pico-amperemeter on the ground return of the tube. The typical d.c. current characteristics are shown in fig. 1, while the dark current response, obtained without illumination, is given in fig. 2. The tube appears rather stable in operation up to above 400 V and in a wide range of light fluxes; a current gain around 20-30 is obtainable safely. From observations made on the pulsed operation (see below), it is suspected that the reason for the discharge lies in the internal mounting geometry of the electrodes (not conceived for operation in a gas) rather than in a secondary photocathode effect, which probably would appear at even higher gains.

It should be noticed that the voltage at which a gain of ten is observed would lead, for the specified pressure of 2×10^{-2} Torr, to unphysical values of the reduced field ($\sim 10^6$ V cm⁻¹ Torr⁻¹). From the known values of the first

*) HP 5082.

Townsend coefficient in argon [5] we would infer a real gas-filling pressure of a few Torr.

To study the pulsed characteristics of the tube, the light-emitting diode was excited with an external generator, whose frequency, width, and amplitude could be varied over a wide range. In this case, the signal was observed on the electrodes using a simple, three-transistor charge amplifier with a high-impedance field-effect input transistor*); the best signal-to-noise ratio was obtained by applying a positive operating voltage to the anode (through a 1 M Ω protection resistor), and connecting the amplifier to the grounded photocathode. The amplifier had a typical noise figure of 1500 electrons FWHM on a 10 pF source; because of the characteristics of the signal, a 1 μ s shaping constant was found adequate.

Figure 3 shows the evolution of the detected charge signal for three increasing values of the operating potential; the horizontal scale is 500 ns/div. The lower pulse, corresponding to $V_0 = 10$ V (collection without multiplication), has a rise-time of about 100 ns, corresponding to the duration of the light flash, followed by the decay-time of the charge amplifier. At the onset of charge multiplication, most of the signal is due to the motion of positive ions within the avalanche, and therefore the signal rise-time decreases. Again, from the known mobility of argon ions ($\mu_0 \approx 1.4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ under normal conditions [6]) one can justify the observed ion collection-time of about 2 μ s only by assuming a gas-filling pressure around 1 Torr, in contrast with the manufacturers' specifications.

The pulsed gain characteristics, measured with a 2 μ s integration and differentiation constants, are shown in fig. 4; the curve reproduces almost identically the d.c. characteristics, and does not appear to be affected by the pulsing rate up to several hundred kHz; above this frequency the signals begin to overlap, making it difficult to measure pulse heights, but no indication of space-charge effects has been obtained.

*) Developed at CERN by J.C. Santiard.

The noise characteristics of the photocathode-amplifier system has been studied by recording pulse-height spectra for low light levels. Although a direct measurement of radiant sensitivity has not been performed yet, the number of photoelectrons collected by the anode for a given light-flash intensity can be computed from the known charge sensitivity of the amplifier (measured by injecting a known charge from a source having a capacitance approaching that of the tube). A typical ungated amplitude spectrum measured for a light-pulse level yielding about 10^3 photoelectrons at $V_0 = 375$ (or 10^4 electrons, the gain being 10 at this voltage) is shown in fig. 5 (rightmost peak; the peak at lower amplitudes represents the intrinsic noise spectrum above the pulse-height analyser discrimination threshold). The FWHM of the distribution is about 25%, corresponding to 2500 electrons; as mentioned, the amplifier noise contributed to the dispersion with 1500 electrons FWHM.

In fig. 6 the measured FWHM of the pulse-height distribution is shown, on the left scale, as a function of the estimated number of photoelectrons, again at a charge gain of 10 for the tube; the fixed electronics contribution is also given. The dashed curve represents instead the relative standard deviation of the same measurement, as given on the right scale.

Even after deduction of the electronics noise, the measured resolution cannot be due only to simple statistical fluctuations in the number of primary photoelectrons; both the light-emission process in the diode and the avalanche charge multiplication are expected to contribute to the measured width, although at this point the relative relevance of each of them is not known. Still, at the level of 10^4 photoelectrons and a gain of 10 in the gas photodiode, the relative standard deviation is 3.4%, which is remarkable for such a device.

Based on the described results, we are now investigating the possibility of implementing a tube operating at higher gas pressures, i.e. approaching and perhaps equalling the atmospheric one. There is no *a priori* reason why such a device should not provide similar performances, once the problems connected with

the gas purity at such pressures are solved. Indeed, both the photon feedback and the positive-ion secondary-extraction processes, which are found to set a natural limit to the gain attainable in such a detector, should if anything be suppressed by the higher gas density. If that is so, the way may be open to the manufacture of large-area, thin-window gaseous photodiodes with moderate gain to fulfil the needs indicated in the Introduction.

As a concluding remark, let me mention that a thin-gap gas photodiode is, as well as its vacuum counterpart, relatively insensitive to strong magnetic fields and can be installed inside or close to analysing magnets; moreover, positioning of the charge within the active area could be implemented by padding the electrodes, by using charge division on resistive electrodes [10], or with special interpolating electrode geometries [11].

REFERENCES

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- [5] S. Brown, Basic data of plasma physics (Wiley, New York, 1959).
- [6] See, for example, E. McDaniel and E. Mason, The mobility and diffusion of ions in gases (Wiley, New York, 1973).

Figure captions

- Fig. 1 : Current gain for uniform illumination of the gas photodiode, as a function of the anodic potential.
- Fig. 2 : Dark current as a function of anodic potential, for room-temperature operation.
- Fig. 3 : Pulsed operation characteristics, at increasing values of the operational voltage on the photodiode. The horizontal scale is 500 ns/div.
- Fig. 4 : Pulsed gain characteristics, measured with a 2 μ s integrating amplifier, versus anodic potential.
- Fig. 5 : Ungated pulse-height spectrum for an estimated flash of 10^3 detected photoelectrons at a tube gain of 10 (right peak). The FWHM of the distribution is about 25%.
- Fig. 6 : The measured FWHM of the pulse-height distribution, as a function of the estimated number of photoelectrons at a diode gain of 10; the fixed electronic noise contribution is shown (left scale). The relative standard deviation is also shown by the dashed curve (right scale).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6