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**READOUT OF OPTICAL SCINTILLATION FIBRES
BY A POSITION-SENSITIVE PHOTOMULTIPLIER**

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ABSTRACT

The present status of a position-sensitive photomultiplier is surveyed, with the aim of applying such a device to a high-rate apparatus in combination with optical scintillation fibres. A spatial resolution of ≈ 1.1 mm (FWHM), obtained with a single fibre of 1 mm diameter, would allow the setting up of a linear array, 180 mm wide, with a spatial resolution of ≈ 1 mm which can be read out by a single photomultiplier tube of this type. Also presented are the important improvements foreseen for the present tubes, based on the scaling property of the Lorentz equation describing the motion of electrons.

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1. INTRODUCTION

The detection of elementary particles with high resolution in time and space is one of the most fundamental subjects of technical development in the field of nuclear radiation detectors.

For a long time, several approaches have been tried in high-energy experimental physics in order to treat phenomena of ever-increasing complexity that are observed as the energy and the intensity of accelerators become higher and higher.

In 1979, a new type of photomultiplier [1] was realized, with the purpose of adding a new dimension — ‘position sensitivity’ — to the classical photomultiplier technique, which is still widely employed thanks to the intrinsic merits of the secondary emission phenomena, e.g. good time resolution, high gain, low noise, etc. Since that time a number of studies carried out on the prototype have revealed its excellent performance, not only in the localization of high-energy particles [2, 3] but also in the field of imaging using low-energy γ -rays [4, 5] and thermal neutrons [6].

Among a number of possible applications for such a device in high-energy physics, we present in this paper the feasibility of constructing a new type of scintillation hodoscope or vertex detector, in view of the recent progress in optical scintillation fibres.

2. TIME CHARACTERISTICS

The position-sensitive photomultiplier (multi-PM) is characterized, in particular, by its simple dynode structure consisting of fine parallel grids (see fig. 1). The secondary electrons are localized, in the plane perpendicular to the principal axis of the tube, by means of a weak axial magnetic field (300–400 G).

After a multiplication of 10^6 – 10^7 , the electrons are captured by a two-dimensional array of anode cells (16 or 88 cells of 2.9×2.9 mm²). Thanks to this simple dynode structure, which provides an almost linear propagation of signal from the photocathode to the anode, the transit time is of the order of only 20 ns for 10 dynode stages, compared with 30–40 ns for most of the conventional high-speed tubes.

Another important feature is a high counting-rate performance comparable to or even higher than that of conventional tubes, thanks to the local excitation of the sensitive volume by individual events. Figure 2 shows the pulse shape of a single anode cell for different frequencies of a pulsed light-emitting diode (LED). The pulse height remains almost constant up to 20 MHz; the abrupt decrease above this value seems to be due to the time characteristic of the LED. Knowing that the secondary electron flux from a single light-spot is distributed over three or four anode cells on the average, the above performance corresponds to a rate of about 100 MHz for a tube of 16 cells.

The resolving time has also been measured with a 16-anode prototype pulsed by a LED. Figure 3a presents a coincidence curve between the signal of the multi-PM and that of the LED generator. This time is about 1.6 ns compared with 0.9 ns obtained under the same conditions with a high-speed conventional tube, XP2020 (fig. 3b). Taking into account the result of a Monte Carlo calculation simulating the secondary electron trajectories inside the dynode system, a non-negligible fraction of this spread seems to be affected by the entrance optics, which still remains in a preliminary stage of development.

3. LOCALIZATION PROPERTIES

Information from the multianode cells can be treated in different ways according to the specific applications. The flux of secondary electrons from a single light-spot spreads over several adjacent cells with a FWHM of 3–4 mm in both the x and y directions. A precise reconstruction of the impact point is obtained from this spatial information by means of the moment method, or with the aid of the interpolation property of a suitable delay line [7]. The precision of such a reconstruction depends,

in general, on the number N of available photoelectrons per event as shown in fig. 4, and can be well described by a semi-empirical relation,

$$\Delta x \approx w_0/\sqrt{N}, \quad (1)$$

where w_0 , the natural width of the multi-PM, is typically 5–6 mm in FWHM.

In the case of high-luminosity events, such as those produced by thermal neutrons on $\text{ZnS}({}^6\text{Li})$, the spatial resolution easily attains ≈ 0.1 mm (FWHM) providing, for example, more than ≈ 6000 equivalent pixels over a small sensitive area ($8 \times 8 \text{ mm}^2$) [6].

The main difficulty of applying such a device in the field of high-energy physics comes, in fact, from the low photon yield of events generally detected through thin scintillation materials or low-density Cherenkov-light media.

In order to see the limit of application in the actual state of the art, we recently performed a series of preliminary measurements of spatial resolution by using a single scintillation fibre of 1 mm diameter. The set-up is schematically illustrated in fig. 5 for two modes of light collection: a) with single-edge contact and b) with double-edge contact. In both cases, in order to simulate relativistic particles passing through the fibre, the low-energy part of the β -ray spectrum was cut off with the aid of an auxiliary counter in coincidence, placed behind a suitable absorber. Figure 6 shows spatial resolutions obtained with single-edge contacts for different distances l between the edge and the irradiated point (0.5–2.0 m). The resolution varies from ≈ 1.5 mm to ≈ 2.0 mm, roughly indicating a number of effective photoelectrons in a range of 5 to 10 following eq. (1). The attenuation of the scintillation light is also estimated to be about 3 dB/m (dotted curve). The resolution can be improved by the double-edge contact, and further by making several loops of fibre so that the incident particles pass successively through n sections of the fibre. A typical example of results obtained with this configuration is shown in fig. 7 for double loops. The resolution is about 1.1 mm in FWHM, which is already close to that imposed by the diameter of the fibre itself. It is worth mentioning that, within the limit of the light attenuation inside the scintillation fibre, the multiloop configuration plays, to some extent, the role of an optical funnel allowing the output section of the scintillator to be reduced without violating the Liouville theorem.

Note also that the whole length of the loops will be incorporated in the sensitive area in case of application to a polar angle detector with 2π geometry.

4. READOUT OF A LINEAR ARRAY OF SCINTILLATION FIBRES

Design of the readout mode requires some practical considerations owing to the two-dimensional cross-talk between the anode cells. Figure 8 shows an example of mapping a linear array onto the two-dimensional array of 88 anode cells, arranged inside the large-size prototype shown in fig. 1. The peripheral cells are used as dummies in order to avoid the edge effect—due to the lack of information from the adjacent cells—in the reconstruction of the impact point. Each ‘effective cell’ contains about three pairs of fibre ends with a distance $d = 2.9$ mm between the adjacent lines, so that a total length of ≈ 180 mm can be read out by a single tube.

Based on the ≈ 1.1 mm accuracy of reconstruction obtained by the double-loop configuration, the confidence level (CL) of the line-number assignment will be better than 99.7% ($d/2 > 3\sigma$).

However, a complication may arise from multiplicity events giving multiple hits on the sensitive area. Following a detailed analysis of such events [8], multihits can in principle be reconstructed with the aid of the higher-order moments, provided that the shortest distance between them is greater than w_0 . In the present arrangement of fibres, the most critical situation may occur when two hits fall inside an area defined by a single column and two adjacent lines; however, the probability that this will happen is quite low.

Let us now try to obtain a rough estimate of the probability of discriminating such a multiplicity event under some reasonable assumptions. Following our previous results [3] with a scintillation hodoscope, the distribution of the second-order moment $\Sigma_2(1)$ for single-hit events is Gaussian-like with a FWHM of $\approx 10\%$ of the average value of w_0 (≈ 5 mm). Note that, as in ref. [3], N was also between 20 and 30 photoelectrons.

Assuming that the second-order moment of the double-hit events is centred on $\Sigma_2(2) = \sqrt{(w_0^2 + d^2)} \approx 5.8$ mm, also with a spread of $\approx 10\%$, the distributions $\Sigma_2(1)$ and $\Sigma_2(2)$ overlap slightly; this is illustrated schematically in fig. 9. Imposing a suitable lower cut on this quantity, say at $\Sigma_2(x) = 5.4$ mm, and assuming also that the frequencies of the single- and double-hit events are *a priori* comparable^{*)}, the event x is considered as multiplicity 1 with a CL of $\approx 95\%$, although the same event might be a single-hit event with a probability of $\approx 5\%$. This ambiguity can be greatly reduced by a cross-check of the first-order moment, i.e. the y -coordinate, because double-hit events should be located around the middle of the adjacent lines. When double-hits have been produced by particles depositing the same amount of energy, the zeroth-order moment (energy sum) provides also a strong constraint, within the limit of the Landau fluctuation, on the selection of double-hit events.

As a matter of fact, this kind of ambiguity is not a proper feature of the cross-talk, but is a general problem which happens in any type of multidetector when the probability of multihits inside the natural dimensions of the detector element becomes non-negligible.

Readout of anode signals may be done in different ways: for example, by splitting each anode cell into three outputs and summing up the cells in the same lines, columns, and diagonals so as to define x -, y -, and u -coordinates, a complete set of information can be read out with $10 + 10 + 15 = 35$ ADCs, which allows the reconstruction of coordinate pairs for a multiplicity event.

When the multiplicity is low, the x -coordinate and the line number ($j = 1, \dots, 10$) may be read out by simple delay lines [7]. A hybrid system is also conceivable for a medium degree of multiplicity, which consists, for example, of delay lines for x -coordinates and ADCs for y -coordinates.

5. POSSIBLE IMPROVEMENTS

Considerable improvements, not only in the localization property but also in the time characteristics, can be foreseen from a simple consideration of the motion of the electrons inside electric and magnetic fields. The original concept of a multi-PM is, in fact, based on the invariant property of the Lorentz equation

$$\mathbf{F} = m_e (d^2\mathbf{r}/dt^2) = e\mathbf{E} + e\mathbf{v} \times \mathbf{B}$$

under the following transformation of variables:

$$\mathbf{r}' = \mathbf{r}/k, \quad t' = t/k, \quad \mathbf{E}' = k\mathbf{E}, \quad \mathbf{B}' = k\mathbf{B},$$

which means that by increasing the scaling factor k , all phenomena observed in space and time will be reproduced exactly on the new reduced scale. This property has the following important consequences for photomultipliers:

- i) better localization of secondary electrons owing to $\mathbf{r}' = \mathbf{r}/k$;
- ii) improvement of all the time characteristics owing to $t' = t/k$;
- iii) improvements in the gain linearity thanks to the higher electric field $\mathbf{E}' = k\mathbf{E}$, reducing the space-charge effect;

^{*)} This depends on the average multiplicity of hits inside the sensitive volume in question (= 2 cells in the present case).

iv) immunity to any type of magnetic field owing to $\mathbf{B}' = k\mathbf{B}$.

These merits show up clearly in a series of modern photomultipliers, such as R1652, R2238, R1911-01, etc., recently commercialized by Hamamatsu Photonics.

Concerning the position-sensitive photomultiplier, significant improvements are actually foreseen in two directions; elimination of the associated magnetic field; and scaling down of the grid structure. Objective (i) can be achieved by combining the proximity-photocathode with a closer structure of the dynode system. Following our estimates and some experimental trials [9], a w_0 of about 10 mm can be obtained, without a magnetic field and with grid bars of the present size (≈ 0.5 mm).

On the other hand, it has been confirmed experimentally that a scaling down of the grid bars by a factor $k \approx 10$ can be achieved using the photo-etching procedure.

By combining these improvements it is therefore possible to envisage—without seeking any as yet unexploited technique—a new position-sensitive photomultiplier having several times better resolutions in time and space, and which would eventually provide the best solution to the problem of multiplicity events.

6. CONCLUSION

In this paper we have described the present status of a position-sensitive photomultiplier, and have suggested a possible application in high-energy physics, in combination with optical scintillation fibres. Using the already existing prototype it will be possible to realize a linear array ≈ 180 mm wide, with a spatial resolution of ≈ 1 mm. Such detector elements, followed by fast electronics, could be conveniently used for constructing, for example, a position-sensitive trigger system with high spatial resolution, a high-resolution electromagnetic calorimeter, etc.

A complication arises, however, when treating high-multiplicity events producing more than two hits within a distance smaller than the natural width w_0 (at present ≈ 5 mm) at the level of the photocathode.

Significant improvements, not only in the spatial performance but also in the time characteristics, can be foreseen from a simple consideration of the scaling property of electron trajectories. A number of facts confirming these effects lead us to believe that in the frame of the already well-established photomultiplier technology it is possible to realize—both quickly and successfully—a new type of photomultiplier which will be far better than the present one in both time and spatial resolution.

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REFERENCES

- [1] K. Kuroda, D. Sillou and F. Takeutchi, Rev. Sci. Instrum. **52** (1981) 337.
- [2] J. Ditta, D. Sillou, A. Michalowicz, H. Azaiez and K. Kuroda, Nucl. Instrum. Methods **220** (1984) 343.
- [3] J. Ditta, K. Kuroda, A. Michalowicz, C. Nemoz and D. Sillou, Nucl. Instrum. Methods **A240** (1985) 69.
- [4] K. Kuroda, Nucl. Instrum. Methods **A241** (1985) 581.
- [5] C. Nemoz, J. Ditta, K. Kuroda and D. Sillou, Nucl. Instrum. Methods **A241** (1985) 588.
- [6] A. Bussière, D. Feltin, B. Hamelin, J. Jacobé, K. Kuroda, P. Liaud, A. Michalowicz, C. Nemoz and D. Sillou, Nucl. Instrum. Methods **A254L** (1987) 215.
- [7] J. Ditta, K. Kuroda, C. Nemoz and D. Sillou, Nucl. Instrum. Methods **A250** (1986) 539.
- [8] C. Nemoz, Ph.D. thesis, Univ. of Grenoble, April 1985, unpublished.
- [9] H. Kume, S. Suzuki, J. Takeuchi and K. Oba, IEEE Trans. Nucl. Sci. **NS-32** (1985) 355.

Figure captions

- Fig. 1: Multi-PM with 88 anode cells.
- Fig. 2: Oscillograph view of pulses at high counting rates.
- Fig. 3: Time resolution obtained with a LED for a) Multi-PM, $\approx 1,6$ ns, b) XP2020, ≈ 880 ps.
- Fig. 4: Spatial resolution as a function of intensity of the light source.
- Fig. 5: Experimental set-up for measuring the spatial resolution with a single scintillation fibre.
- Fig. 6: Spatial resolution for different distances between the irradiated point and the light-output edge.
- Fig. 7: An example of spatial resolution obtained with the double-edge contact and double-loop configuration. a) Two-dimensional (x-y) histogram; b) x-projection of histogram (a).
- Fig. 8: Mapping of linear array of fibres onto a two-dimensional array of anode cells.
- Fig. 9: Principle of discriminating double-hit events from single-hit ones by means of the second-order moment Σ_2 .

Fig. 1

Fig. 2

Fig. 3

Fig. 4

a) Single-edge contact

b) Double-edge contact

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9