EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/90-90
29 June 1990

**A SCINTILLATING-FIBRE HODOSCOPE USING A
POSITION-SENSITIVE PHOTOMULTIPLIER**

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ABSTRACT

Along with recent progress in the scintillating-fibre technique, the readout device is also gaining increasing importance in the field of detector research and development.

In this paper we present a prototype scintillating-fibre hodoscope read out with a position-sensitive photomultiplier, which demonstrates a good performance for a variety of applications such as particle physics and biological imaging.

The paper presents also a new method of handling, in real time, the space information coming from such types of modern photomultiplier tubes.

(Submitted to Nuclear Instruments and Methods in Physics Research)

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1. INTRODUCTION

Recent progress in the scintillating-fibre (SciFi) technique has made it possible to conceive new types of detectors, in particular for particle tracking and for the calorimetry of photons and hadrons. Among the several types of readout devices, position-sensitive photomultipliers (PSPMs) [1] will be potentially of great importance in future high-energy detectors, thanks to their inherent advantages: high gain with good linearity, low noise, and excellent time characteristics, in addition to their simple and dependable operation.

The combination of SciFi and PSPMs has recently been studied by several authors [2], using different methods of signal handling; for example, coding of the hit position by a combination of independent anode cells [3], or reconstruction of the hit position by means of the centroid of pulses coming from multianodes that are related to each other by cross-talk.

During the last several years, we have been studying a readout system of SciFi based on a delay-line method [4], which seems to be the best way of digitizing the hit position essentially in real time [5].

In this paper, we present a prototype SciFi hodoscope, recently built and tested at CERN.

In addition to the experimental results, we briefly describe in Section 3 a 'real-time digitizer' (RTD) that would have a wide range of applications, in particular in future collider experiments. One of the essential advantages of such a digitizer is the simultaneity of the digital outputs, which was experimentally confirmed as shown in Section 4.

2. DESCRIPTION OF THE PROTOTYPE

The mechanical structure of the detector is shown in figs. 1a to 1c. The sensitive area, 96 mm in width, consists of an array of SciFi, each fibre being 1 mm in diameter. The SciFi, produced by OPTECTRON, have an aluminium coating so as to avoid optical cross-talk between the fibres. As shown in fig. 1a, the array consists of four overlapping sublayers, so that the effective thickness for incoming particles is about 2 mm at any position. To match the full width of the detector to the sensitive area of the PSPM^{*)} photocathode, the SciFi array is divided into four segments, 24 mm wide, and the fibres of each segment extend by about 20 cm to the PSPM photocathode where the segment is stretched out over 32 mm, which is the available width on the photocathode; the four segments are spaced by 12 mm so that the cross-talk between the corresponding anode wires in the Y direction is almost negligible (a few per cent). Figure 1c shows the SciFi array mounted inside a housing, together with a PSPM. The whole assembly is as compact as an ordinary scintillation counter.

Figure 2 shows the arrangement of the four arrays on the PSPM and a block diagram of the associated electronics performing two separate functions: i) reconstruction of the hit position by means of a time-lag method; ii) digitization of the hit position in real time (see RTD in Section 3).

For the current tests, the hit position inside a segment has been reconstructed by measuring the time lag between Start and Stop signals coming from constant fraction discriminators (CFDs) connected to the ends of delay line 1 ($D \approx 44$ ns). The number of the fired segment is given by a slow coincidence between the Stop signal and that of the corresponding anode wire in the Y direction. According to the number of fired segments, the Stop signal is delayed by a step of D ns so as to display the full distribution of events in a single histogram. Figure 3 is an example of such an event distribution, which consists of four parts (A, B, C, and D) located side by side with a slight overlap.

*) The tube used for the prototype (R2486-01, Hamamatsu) has 32 crossed anode wires (16 in each direction, X, Y) with a step of 3.75 mm.

With two planes of hodoscopes, two-dimensional plots of hit positions can be obtained on a cathode-ray tube (CRT) display by using time-to-analog converters (TACs). The time lag information coming from the first part of the electronics can also be either read out by using a TDC or directly digitized by using an RTD to make a fast position-sensitive triggering.

3. REAL-TIME DIGITIZATION

The functional diagram of the RTD is illustrated in fig. 4. In this scheme the CFDs are omitted and signals are presented, along the whole loop of a delay line 2D, as if they were normalized in width and height. As shown in fig. 4a, the signals propagating towards the left (L) and the right (R) meet again in the lower part of the loop, and the folded pulse comes out through one of the discriminators corresponding to the hit position. Different phases of this transition are visualized in fig. 5 by a series of oscilloscope views showing the left and right pulses at the inputs of the successive discriminators.

It should be pointed out that the transit time, $T_{out} - T_{in}$, is always equal to D independently of the hit position. This simultaneity of the digital outputs makes further handling of multihit events easier, as illustrated in fig. 4b. For example, for a double-hit event there are four combinations of the left and the right pulses, which give four folded pulses, each exceeding the threshold of the discriminators. However, if the double hits are separated by Δt on the delay line, the transit time for the bad combinations, i.e. $L(1) + R(2)$ and $L(2) + R(1)$, is shifted by $\pm \Delta t/2$, so that the false positions can be eliminated by making a coincidence of the output signals, with a suitable reference time given, for example, by the last dynode or by an external counter.

The two-hit resolution is limited, at present, not only by the intrinsic time and space resolutions of the commercially available tubes, but also by the pulse-pair resolution of the available CFDs. An improvement in this respect will enhance the capability of handling multihit events, which is essential, in particular in the field of future collider experiments.

Referring again to fig. 2, the digitizer used in this study consists of a delay line, equivalent to the first one (~ 44 ns), on which a series of 12 discriminators are connected, by a step of 4 ns, through an impedance adaptor in each channel. Such a scheme is flexible: it can adjust the binning width by means of the incoming pulse width and the thresholds of the discriminators. For example, a bin width of 6 ns for a binning step of 4 ns provides a final binning resolution of 2 ns. This is similar to the mechanical superposition of scintillator strips currently employed in ordinary hodoscopes. On the other hand, by clipping the output pulse of the CFD, it is possible to obtain a finer binning, with good stability, down to ~ 0.8 ns, which corresponds to ~ 0.4 mm at the level of the fiducial area.

4. EXPERIMENTAL RESULTS

The prototype has been tested in several runs with different radiation sources: 2 GeV/c positive particles from the CERN Proton Synchrotron (PS), as well as a 200 MeV/c negative beam^{*)} from the Synchrocyclotron (SC). Some calibrations have also been done in the laboratory by using a ^{90}Sr β -source. The results presented below come mostly from a recent test carried out at the SC, unless otherwise specified.

4.1 Detection efficiency

Our first care was for the detection efficiency of the prototype, because only 10–15 photoelectrons can be expected for a minimum-ionizing particle traversing the ~ 2 mm effective

^{*)} The beam composition was: 55% e^- , 12% μ^- , and 33% π^- .

thickness of the SciFi array. Figure 6 is an oscilloscope view of the signal produced by 2 GeV/c particles, at the input of one of the CFDs. In spite of a broad spectrum ($\sim 300\text{--}800$ mV, by amplification of approximately $\times 100$), the signals are clearly separated from the photomultiplier noise, which is scarcely seen below 100 mV. The threshold curve, presented in fig. 7, has in fact a plateau extending up to ~ 200 mV, as expected from the spectrum.

The local detection efficiency was carefully studied, using a beam of higher intensity ($\sim 10^5/\text{s}$) from the SC. The incident particles were defined by two fine counters (S1 and S2), 0.5 mm wide, placed at ~ 3.5 cm upstream of and downstream from the SciFi array. The efficiency after digitization was calculated from the sum of all the digitized bins (1 to 12), ΣN_{digit} , normalized by the incident flux defined by the coincidence $S1 \cdot S2$. In addition, in order to check false assignments of the digitized position that are due to accidental backgrounds at the level of the upstream slow coincidences, a fast coincidence (~ 10 ns) was imposed between the sum of all the digitized bins ΣN_{digit} and $S1 \cdot S2$. Note that the signals from the CFDs are already filtered by $S1 \cdot S2$, but with a loose coincidence (~ 100 ns) since their time lag depends on the impact position.

Figure 8 presents both quantities, $\Sigma N_{\text{digit}}/S1 \cdot S2$ and $(\Sigma N_{\text{digit}}) \cdot S1 \cdot S2/S1 \cdot S2$, as a function of the position of the definition counters. The final efficiency thus defined is about 95% over the full range, except for narrow gaps between the adjacent segments. This effect, which is discussed in Section 5, comes mostly from the mechanical structure of the SciFi array at the boundaries of the segments and could be suppressed by rearranging them. Also, the additional fast coincidence kills the $\sim 5\%$ of ΣN_{digit} that may arise from background, giving bad combinations of the left and right signals from delay line 1.

4.2 Space resolution

A typical example of event distributions displayed on a QVT module is presented in fig. 9. The peaks come from the accumulation of events at different positions of the beam defined by $S1 \cdot S2$. The space resolution is estimated to be as good as $\sim 1.1\text{--}1.2$ mm in FWHM, depending slightly on the hit position.

The digital outputs, as well as flags A to D, have also been recorded in an on-line computer through the CAMAC system. Figure 10 is a histogram, corresponding to fig. 9. It is reconstructed by an on-line program, taking into account the number of fired segments as well as the adjacent hits to be classified into interposed bins. The binning width has initially been adjusted so as to have approximately equal numbers of single-hit and adjacent-hit events over the full sensitive area. The intrinsic resolution of the digitizer circuit thus becomes about 1 mm per bin.

4.3 Linearity

The linearity of the reconstructed position was studied by moving the beam counter $S1 \cdot S2$ by a step of 5 mm along the X direction. As seen in fig. 11, the overall linearity is quite good, but there exists a slight local irregularity, in particular across the gaps between the adjacent segments.

4.4 Resolving-time

The simultaneity of the digitized outputs was checked under a wide event distribution of β -rays from ^{90}Sr . Figure 12 shows an example of a coincidence curve between ΣN_{digit} and the signal of a Y-anode (Y10) as a reference time. As described in Section 3, the time fluctuation of the anode signals—as much as ~ 44 ns—is effectively compensated, and the resolving-time becomes as short as ~ 10 ns, a time spread that corresponds to the pulse width of the incident signals into the coincidence circuit. The asymmetry of the tails is not thoroughly understood, but it seems to be due to a bias on one of the false combinations, introduced by the dead-time of the CFDs.

4.5 Two-dimensional images

After having checked the basic characteristics of the prototype, we carried out a visualization of two-dimensional images by using two identical hodoscopes oriented one along the horizontal plane and the other along the vertical plane. The Start and Stop signals in each plane were sent to the on-line computer through a four-channel TDC. Figure 13 shows an example of an image obtained with 200 MeV/c particles, and defined by an external counter having several pieces of plastic scintillator shaped in the form of letters. Also shown, on the upper right-hand side, is the result of a scale calibration performed with S1 · S2 moved along the X direction by a step of 10 mm. The letters therefore occupy a surface of $\sim 40 \times 80 \text{ mm}^2$. Both coordinates are normalized for direct comparison.

The image quality is good enough, not only for the first-stage application to our Fermilab experiments but also for some other applications, such as biological imaging using β -rays as proposed by Chalon et al. [3]. The higher background in the lower image may arise from a loose coincidence introduced only between one of the hodoscope planes and the image-definition counter.

5. DISCUSSION

From the encouraging results presented above we consider the prototype to be already at the stage of practical use. Nevertheless, a few improvements have still to be made in order to remove, in particular, the problems of

- i) fine structure in the local counting rates;
- ii) defects in the detection efficiency in the critical zones between adjacent SciFi segments.

The former shows up especially when looking at a quasi-flat distribution such as that in fig. 14. Apart from the dips between the segments, there is also a local variation of counts, characterized by a common structure for all the segments. Such a variation cannot be explained by the detection efficiency having a fairly flat structure outside the critical zones (see fig. 8). It is therefore considered as a fine structure coming from a non-linearity of the reconstructed position, or, in other words, from a local variation of the space resolution. Such a structure may come, for example, from an irregularity of the local gain, or a deformation in the effective position of anode wires^{*)}. For this reason, our present work is oriented towards a fine adjustment of delay line 1 by taking into account these possible faults that are relevant to individual PM tubes.

After all, the global effects of such a fine structure on the physics quantities—scattering angle, momentum of particles, etc.—seem, in general, to be fairly unimportant simply because of the statistical nature of the measurements.

The second problem is related to the mechanical structure of the SciFi array. As seen in fig. 1a, the successive sublayers overlap one another by $\sim 0.15 \text{ mm}$, so that there is no dead space left for the incoming particles falling perpendicularly onto the layers. When a particle hits the extreme fibres of one of the segments, it hits the extreme fibres of the adjacent segment simultaneously, so that the scintillation light is split into the two opposite extremities of these segments. This gives a double pulse on the delay line, and the CFDs are ‘often’ triggered at the middle of the double pulse. This disadvantage should be removed, in the future, by improving the time characteristics of the elements concerned.

A simpler solution actually foreseen would be to alternate the sense of the readout direction of the SciFi, from segment to segment, so as to avoid splitting the scintillation light at the extremities of the segments.

*) A slight irregularity in the geometric dynode structure might produce a significant lateral deviation of the secondary electron flux during the multiplication process, and affects the effective position of anode wires ‘seen’ at the level of the photocathode.

6. CONCLUSION

We have constructed and tested a new type of hodoscope, which consists of a SciFi array and PSPMs both considered to be promising materials in the field of new detector R&D thanks to their excellent timing characteristics.

A hodoscope of this type is at present used in the Tevatron polarized beam at Fermilab, for a small-angle polarization measurement [6].

Apart from a few improvements that are still to be made, we confirmed a very encouraging performance of the basic characteristics, such as

space resolution: ~ 1 mm in FWHM over 96 mm,
detection efficiency: ~ 95%,
resolving time: ~ 10 ns,
etc.

The real-time digitization, conceived and preliminarily tested in this work, has the possibility of profiting fully from the excellent timing characteristics of the new components used.

The faculty of handling the multihit events was not confirmed in the present study, but it will be demonstrated in the near future by the ever-progressing technology in the field of PSPMs and in that of fast electronics.

Finally, it should be emphasized that, compared with other types of SciFi readout devices such as image intensifiers followed by charge-coupled devices (CCDs), the PSPM associated with our digitizer is distinguished by its unique capability of integrating the spatial information into the first-level criteria for the event selection.

Acknowledgements

We are very grateful to all the members of the CERN SC group, who offered us the beam facilities under the best conditions. We thank our colleagues of the Fermilab Collaboration for their constant interest and encouragement, as well as for their enlightening comments. We are also much indebted to the technical staff, and in particular to J. Ditta and H. Vey, for their efficient assistance.

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Figure captions

- Fig. 1: Mechanical structure of the SciFi hodoscope.
- Fig. 2: Associated electronics.
- Fig. 3: Event distribution over the full range of the sensitive area.
- Fig. 4: Principle of the real-time digitization.
- Fig. 5: Oscilloscope views of the left and right propagating pulses, seen at the inputs of successive discriminators of the digitizer.
- Fig. 6: Oscilloscope view of signals from delay line 1.
- Fig. 7: Threshold curve of the signals from delay line 1.
- Fig. 8: Local detection efficiencies: $\bullet (\Sigma N_{\text{digit}})/S1 \cdot S2$; $\circ (\Sigma N_{\text{digit}}) \cdot S1 \cdot S2/S1 \cdot S2$.
- Fig. 9: Measurements of the space resolution.
- Fig. 10: Histogram of the digitized events.
- Fig. 11: Linearity of the reconstructed position.
- Fig. 12: Coincidence curve showing the simultaneity of the digitized outputs.
- Fig. 13: Two-dimensional images obtained with two identical hodoscopes displayed in the X and Y directions.
- Fig. 14: A typical example of quasi-flat distributions, affected by local variation of the linearity.

Fig. 1

Fig. 2

Number of events

Reconstructed position on QVT

Fig. 3

a) Single-hit event

b) Double-hit event

Fig. 4

→ ←
20 ns

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14