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HIGH RESOLUTION TIME-OF-FLIGHT MEASUREMENTS
IN SMALL AND LARGE SCINTILLATION COUNTERS

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ABSTRACT

In a test run, the experimental time-of-flight resolution was measured for several different scintillation counters of small ($10 \times 5 \text{ cm}^2$) and large ($100 \times 15 \text{ cm}^2$ and $75 \times 25 \text{ cm}^2$) area. The design characteristics were decided on the basis of theoretical Monte Carlo calculations. We report results using twisted, fish-tail, and rectangular light-guides and different types of scintillator (NE114 and PILOT U). Time resolutions up to ~ 130 - 150 ps FWHM for the small counters and up to ~ 280 - 300 ps FWHM for the large counters were obtained. The spatial resolution from time measurements in the large counters is also reported. The results of Monte Carlo calculations on the type of scintillator, the shape and dimensions of the light-guides, and the nature of the external wrapping surfaces -- to be used in order to optimize the time resolution -- are also summarized.

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1. INTRODUCTION

For an experiment at the CERN Proton Synchrotron (PS)¹⁾ to search for strange dibaryon systems in the reaction $K^- + d \rightarrow K^+ + \text{missing mass}$ (experiment PS159), very high resolution time-of-flight (TOF) measurements were required with "small" scintillation counters ($5 \times 10 \text{ cm}^2$) to distinguish incident K's and π 's in the 1.4 GeV/c separated beam, and with "large" hodoscope counters (nine scintillators $25 \times 75 \text{ cm}^2$) to identify the positive final product of the reaction $K^- + d$. Typical time separations among particles were $\geq 1 \text{ ns}$.

Consequently we have studied the time resolution available with TOF measurements in several different counter alternatives. This time resolution depends mainly upon

- a) the light pulse at the photocathode: its shape, the number of photons, and their spectral distribution; in other words, this involves the type of scintillator and the counter geometry;
- b) the phototube characteristics (gain, transit time and its jitter, response to a single photoelectron, etc.);
- c) the operative TOF definition (zero crossing, leading edge, constant fraction, etc.).

Preliminary theoretical calculations of light-collection efficiency and pulse shape at the photocathode have been performed using a CERN Monte Carlo (MC) program²⁾. The purpose was to decide which shape and dimension of light-guide and which type of scintillator to use. The scintillator type is mainly characterized by its rise-time ρ , short-component decay constant τ , and light attenuation length λ . The effect of reflecting or absorbing external wrapping surfaces was also studied.

In a test run, the experimental TOF resolution was measured for several different scintillation counters, realized on the basis of the theoretical calculations. In this paper we report the experimental results obtained with twisted, fish-tail, and rectangular light-guides and different types of plastic scintillator (the slow and relatively cheap NE114, and the fast but expensive PILOT U) of several

dimensions. The spatial resolution obtained in the large counters, measured with a system of multiwire proportional chambers (MWPCs), is also reported.

In the Appendix, relevant results of the Monte Carlo calculations are briefly summarized.

2. GEOMETRICAL CHARACTERISTICS OF THE COUNTERS

We have considered several different types of scintillation counter (see fig. 1) and attempted to optimize the characteristics of each of them (e.g. dimensions, outside surfaces treatment, i.e. absorbing or reflecting or diffusing, etc.), based on the results obtained by Monte Carlo calculations, to obtain the best time resolution.

For the "large" hodoscope counters, we considered three different types of light-guide: the simple rectangular one (RT); the trapezoidal "fish-tail"-shaped one (FT); and the "twisted" one (TW). In the TW case an appropriate number of twisted strips allows the connection of the rectangular scintillator surface to a nearly square surface, which is then optically reduced to the diameter of the photomultiplier (PM) (see figs. 1c and 1d). All the guides end with a plexiglas cylinder (8 cm long and 4 cm diameter), which is necessary for the PM assembly.

In order to have counters with high time resolution, we must satisfy the following optical criteria:

- a) A high total light-collection efficiency ϵ_T must be achieved. More specifically, the efficiency ϵ_F for collection of the "fast" photons, which reach the photocathode in the first 1-2 ns from the beginning of the luminous pulse, must be high. In fact the photons which travel over long trajectories ("slow" photons) increase the total electrical charge collected at the anode (i.e. the total pulse height, PH) but do not improve the time definition of the event. On the contrary, the presence of a large pulse tail makes it more difficult to obtain a good "time-walk" correction based on the total pulse height (see later);

- b) The efficiency ϵ should be rather independent of the impact point of the particle in the scintillator, in order to give a good time resolution uniformity throughout the counter.

Following these requirements, the MC results (see Appendix) indicated that the RT-type light-guide should be rejected *a priori* because of the presence of too many "slow" photons. Thus in the test run we have experimentally compared the TW guides and the geometrically simpler FT ones. Figure 1 shows the dimensions of the guides used, which optimize the response of the scintillators according to the previous criteria, following the MC results.

In a normal scintillation counter the outside surfaces are usually reflecting or diffusing to gain photons not trapped in the counter by total reflection. (Later on we will briefly indicate as "aluminized" surface that portion of the counter externally wrapped by a mirror surface -- in our case aluminized mylar.) In the present application, the MC calculations suggest that for better TOF measurements all counters should have absorbing external surfaces (e.g. black paper) except for the final part of the guides. The final cylinder must be "aluminized" in all cases; in addition, the trapezoidal FT guide, and the conical frustum in the TW case, must also be "aluminized" (see fig. 1).

For the "small" beam counters, the RT geometry turns out to be entirely adequate for our purposes.

3. ELECTRONICS

All counters were seen by two PMs situated at opposite ends (see fig. 1). Total light output is increased, thus improving the resolution and, by averaging the signals from the two PMs, the time measurements are nearly independent of the incident position of the particle on the scintillator.

Philips XP2020 PMs (2" photocathode) were chosen as being the best phototubes for our purposes. Typical characteristics are: D-spectral sensitivity; rise-time 1.5 ns; transit-time jitter 0.25 ns; time difference between centre and edge of the photocathode 0.25 ns. The tubes were powered by a type B'

high-voltage divider with typical gain 2×10^7 at 2500 V (see Philips Data Handbook). The last dynodes were blocked by Zener diodes. The supply voltages were chosen to equalize the output amplitudes of each PM for minimum ionizing particles.

LeCroy electronics have been used throughout: 621 CL discriminators, 622 C and 465 coincidence circuits, 2249A ADC (1024 channels, 0.25 pC/ch), and 2228A TDC (1024 channels, 50 ps/ch). The measured logic electronics time jitter was confined within one TDC channel ($\lesssim 50$ ps).

The anode pulse of each PM was split resistively into three signals. The first pulse was fed to the ADC input. The second and the third signals, of the order of 1 V, were sent to two discriminators, according to the Low-High technique. The LOW pulse (output of a 30 mV threshold discriminator) was fed to the TDC and used for the TOF measurements. The HIGH pulse (300 mV threshold), used in the logic, was also fed to a TDC unit and used for off-line rejection of "accidentals" in high-intensity flux conditions ($\sim 10^6$ particles/s). This is described later in more detail. For the trigger logic, the OR of the HIGH pulses from the two PMs of the same counter was utilized. Furthermore, in order to reduce the pile-up at the input of the TDC, the LOW pulse was gated by the logic OR of the same counter.

All information from the TDC and the ADC was sent on-line to a Norsk-Data NORD-10S computer, which recorded each individual event on magnetic tape.

4. TIME-OF-FLIGHT MEASUREMENTS: PULSE-HEIGHT CORRECTIONS AND ELIMINATION OF "ACCIDENTAL" EVENTS

4.1 The TOF between two counters, C_1 and C_2 (see fig. 2), is given by the difference between the average value t_2 of the LOW threshold crossing times for the STOP counter [$t_2 = (t_{2A} + t_{2B})/2$] and the corresponding value t_1 for the START counter [$t_1 = (t_{1A} + t_{1B})/2$].

These values have to be corrected for the "time-walk" of each threshold crossing time, because of the different PH values of the various PMs.

We have performed the correction of each t_j using (after pedestal subtraction) the mean value $\langle A_j \rangle$ of the charge collected from the PMs of counter C_j . It

may be noted that, for the large counters where the light absorption plays an important role, the geometric mean is preferable to the arithmetic one, because it gives a result independent of the position of the impact point. If we assume, as usual (see, for example, ref. 3), a dependence of t_j on $\langle A_j \rangle$ as $t_j \approx k_j / \sqrt{\langle A_j \rangle}$, then the time correction δt_j to be applied is $\delta t_j = k_j [(1/\sqrt{\langle A_j \rangle}) - (1/\sqrt{A_0})]$, where A_0 is arbitrarily chosen near the peak of the amplitude distribution (to reduce uncertainties due to the error in the experimental evaluation of the correction parameters k_j). The actual values of k_j [obtained by a linear fit of $(t_2 - t_1)$ as a function of $1/\sqrt{\langle A_1 \rangle}$ and of $1/\sqrt{\langle A_2 \rangle}$, respectively] gave, typically, $k_j \approx 5 \text{ ns} \times \times \text{pC}^{1/2}$. An iterative correction process on the already corrected values $\overline{t_1}$ and $\overline{t_2}$ was found to be completely unnecessary (see Section 5).

As an alternative procedure, we have also tried a separate correction for the threshold crossing time of each individual PM (e.g. t_{1A}) using the corresponding PH (A_{1A}). It is interesting to note that the TOF $t_2^* - t_1^*$ obtained in this way gave a result completely equivalent to the TOF $\overline{t_2} - \overline{t_1}$ obtained from the previous procedure based on the average PH $\langle A_j \rangle$. This was also found to be true for the counters of large dimensions (see Section 6).

The correction parameters k_j were found to be independent of the point of incidence on the scintillator. So it was possible to apply an identical correction procedure (using the same parameters) for all particles, independent of the crossing point on the counter.

As far as long-term stability is concerned, we have checked, over a period of many months, that the values of the correction constants remained quite stable for all counters if the PMs gain and transit time were kept constant.

4.2 At high flux (we have run up to $\sim 10^6$ particles/s crossing the counters) a spurious particle or a PM noise pulse can produce a START or STOP signal uncorrelated with the real TOF. The contribution from these "accidental" events enlarges the shape of the TOF distribution, and it may also produce fictitious accumulations of events on the time axis.

To drastically reduce such a contamination (thus resulting in a better resolution and cleaner time distributions, and therefore a more reliable separation between different particles), we have used the following criteria:

- i) If the master signal which gives the START to the TDC is driven by the time of the HIGH signal of a single PM (e.g. t_{jA}^H from the C_{jA} PM), the times of the LOW signals from the two PMs, C_{jA} and C_{jB} , must show a strong correlation for physically "good" events. Figure 3a shows, as an example, the two-dimensional plot of the LOW signals t_{1A}^L versus t_{1B}^L : the "good" events are confined in a well-defined blob, while the "accidental" ones are spread over the whole plane. The same elimination procedure has also been applied to counter C_2 , using a different TDC with a START given by the master timed by the output of a single PM of C_2 .
- ii) Moreover for physically "good" events, the time of the HIGH pulse of each PM must be related in a well-defined manner to the time of the corresponding LOW signal. As an example, in fig. 3b the plot of t_{1A}^H versus t_{1A}^L is shown: "good" events lie inside a narrow band at 45° , and the majority of the "accidentals", being outside that region, may be eliminated.

These rejection criteria proved to be extremely valuable in obtaining clean TOF distributions in conditions of high particle fluxes.

5. TIME-OF-FLIGHT MEASUREMENTS WITH SMALL-AREA COUNTERS

The TOF measurements with the "small"-area counters ($10 \times 5 \text{ cm}^2$, see counter S of fig. 1a) were performed with two different types of scintillator: the relatively slow NE114, and the fast PILOT U. In table 1 the physical characteristics⁴⁾ of such scintillators are reported. It should be noted that with regard to the number of available photoelectrons, the scintillator-light spectral response, integrated over the spectral sensitivity function of the XP2020 D-photocathode, favours the PILOT U by a factor of 1.17.

The counters were tested both on a PS pion test beam (t_1) and on a 1.4 GeV/c K^- separated beam (k_{24} beam: π/K ratio ~ 8 , up to a total of $\sim 10^6$ particles/s).

The distance b between the START and the STOP counters, S_1 and S_2 , was ~ 7.5 m. In these measurements we did not use any definition counter (see fig. 2), so the beam illuminated the whole area of the scintillators. The geometry of the counters S_j is shown in fig. 1a; the entire surface was "aluminized", i.e. the whole counter was wrapped with aluminized mylar.

The standard deviations obtained for the TOF distributions with two NE114 counters, 2 cm thick, or PILOT U counters, 1 cm thick, are reported in table 2, where $\sigma(S_2-S_1)$ is the standard deviation of the $(t_{S_2}-t_{S_1})$ distribution; the $\sigma(\overline{S_2}-\overline{S_1})$ refers to the TOF distribution obtained after PH correction; the $\sigma(\overline{\overline{S_2}}-\overline{\overline{S_1}})$ is the result of a further iterative correction process which turns out to be completely unnecessary (for further details, refer also to Section 4.1). The contributions of the single counters, $\sigma_{\text{intr}}(S_j)$, to the resolution are also reported. It can be seen that the 1 cm thick PILOT U counter resolution is only slightly worse than the 2 cm NE114 one.

Figure 4 shows the corrected and uncorrected TOF distributions obtained for the NE114 counters with a π^- beam and for the PILOT U with the separated K^- beam: the PH correction greatly reduces not only the σ but also the width at the base of all the distributions, characterized by the width, $\Delta T_{5\%}$, at 5% of the peak value.

An interesting way to visualize the effect of the TOF pulse-height corrections is the following. For each event we have also measured the PH, $\check{A}\check{C}_0$, of an aerogel Čerenkov counter $\check{C}_0$ used for the hardware π -K separation in the beam. If we compare the plot of $\check{A}\check{C}_0$ versus the uncorrected and corrected TOF for the 1 cm PILOT U counters (see figs. 5a and 5b), the great improvement achieved with the PH correction in the separation between different particles is quite evident.

6. TIME-OF-FLIGHT AND SPATIAL RESOLUTION MEASUREMENTS WITH LARGE-AREA COUNTERS

The TOF resolutions obtained with large-area scintillation counters (100×15 cm² and 75×25 cm², see counters H of figs. 1b, 1c, and 1d) also proved to be very satisfactory, completely fulfilling the requirements of our experiment (good particle separation up to TOF physical distances of the order of ~ 1 ns).

As we did for the "small" counters, in this case also we have tried two types of scintillator: the NE114 and the PILOT U, whose characteristics have been summarized in table 1, Section 5.

The TOF was measured between a "small" ($10 \times 5 \text{ cm}^2$) START counter S and a "large" STOP counter H, $\sim 5.5 \text{ m}$ apart. A small $0.5 \times 0.5 \times 0.5 \text{ cm}^3$ scintillator C was used in coincidence as definition counter (see fig. 2). Measurements were made with particles impinging on either the centre of the counter (CENTRAL POSITION) or the extreme edge of the scintillator, near the light-guide (EDGE POSITION).

The general motivations for the geometrical characteristics chosen for the tested counters (see figs. 1a, 1b, and 1c) have already been discussed in Section 2, and here we report the main experimental results obtained by us.

6.1 First, we have compared two H counters using the same scintillator NE114 ($100 \times 15 \times 3 \text{ cm}^3$), but one connected to 40 cm long "aluminized" fish-tail light-guides and the other using two twisted strips, 40 cm long, and an "aluminized" frustum, 15 cm long, as light-guide (see figs. 1b and 1c for more details). The START, S, was in this case a $10 \times 5 \times 2 \text{ cm}^3$ NE114 scintillation counter.

Table 3 shows the results obtained for the two counters H with particles incident on the scintillator in the CENTRAL or in the EDGE position near to the light-guide. With the same definitions as we used in Section 5, $\sigma(H-S)$ and $\sigma(\bar{H}-\bar{S})$ indicate the standard deviations of the uncorrected and corrected TOF distributions. The $\sigma(H^*-\bar{S})$ refers to the distribution obtained by the alternative procedure of correcting separately the threshold crossing time of each PM of the counter H using the corresponding PH (rather than the usual correction of the average time of the counter t_H in terms of the average PH, $\langle A_H \rangle$; see Section 4 for more details). It is clear that the two different correction procedures give completely equivalent results.

As already defined, the $\sigma_{\text{intr}}(H)$ of table 3 are the contributions of the counters H to the TOF resolution.

The comparison, in table 3, between FT and TW guides is clearly in favour of the latter. This is in good agreement with the MC results, which indicate that

TW guides have higher light-collection efficiency: both the total efficiency ϵ_T and the efficiency for "fast" photons (within ~ 1 ns) ϵ_F (see Appendix).

As a further remark on the data of table 3, we observe, for the FT case, a better resolution at the EDGE near the light-guide than at the CENTRE of the counter. This result qualitatively agrees with the MC calculations, where the FT guide counter shows a small decrease in ϵ_T near the centre (see Appendix, fig. A.3).

Figure 6 shows the TOF distributions measured by the counter H using TW guides, for particles crossing the centre of the NE114 scintillator. As in the case of the "small" counters (see Section 5), both the σ and the width at the base of the distribution are very much improved by the PH correction.

6.2 Secondly, we considered a $75 \times 25 \times 3$ cm³ NE114 scintillator connected at both edges to three, 50 cm long, twisted elements, which transform the 25×3 cm² transverse area of the scintillator into an almost square one, 8.3×9 cm², see fig. 1d.

In table 4 the TOF resolutions obtained in this case are reported. Comparing the results of table 4 with the resolutions of table 3, which refers to the TW guide $100 \times 15 \times 3$ cm³ NE114 scintillation counter, we note that the use in the present case of a three-element TW guide totally compensates the larger losses due to the increased transverse area of the scintillator (now 25×3 cm² instead of 15×3 cm² as in the previous case).

Figure 7 shows the corrected and uncorrected TOF distributions for particles crossing the centre of the considered counter. The usual large improvement in the σ and $\Delta T_{5\%}$, due to the PH correction, is evident.

6.3 Finally, we report the results obtained with an H counter made with a $75 \times 25 \times 2.5$ cm³ PILOT U scintillator and using three, 50 cm long, twisted strips and a 15 cm "aluminized" frustum (see fig. 1d). This is the type of counter we have actually used in the experiment.

In this case the START, S, was given by a 10×5 cm², 1 cm thick, PILOT U scintillation counter.

Comparing the obtained resolutions listed in table 5 for this H counter, with the results of table 4 (which refers to the 0.5 cm thicker NE114 counter having

practically the same geometry), we note that there is no difference in resolution between the 3 cm thick NE114 counter and the more expensive 2.5 cm thick PILOT U one. This result cannot be quantitatively understood on the basis of the theoretical number of photons expected to be collected in the two cases. In fact such a number would clearly be in favour of the PILOT U (see Appendix, fig. A.6), even taking into account the small difference in thickness between the two counters. However, it should be noticed that, when these very high resolution values are reached, it becomes difficult to draw correct quantitative conclusions. In fact at these limits, unpredictable factors which are very difficult to evaluate start to become important. Examples of such factors would be: imperfect mechanical realization of the twisted strips (considered as ideal in all the numerical computations), which can result in different losses of light for different strips; possible imperfect gluing of the scintillator to the light-guides; slightly different characteristics of the PILOT U used, etc.

It can also be seen from table 5 that, for this TW guide counter, the resolution in the CENTRAL position is better than that measured at the EDGE of the scintillator. This is in agreement with the light-detection efficiency MC results, relative to TW guide counters, where the CENTRE appears to be slightly favoured in comparison with the EDGE of the scintillator (see Appendix).

The TOF distribution of fig. 8, obtained with this counter, shows how well two particles, $\lesssim 1$ ns apart, can be separated after PH correction.

6.4 For the H counter ($75 \times 25 \times 2.5$ cm³ PILOT U TW guide counter) considered in Section 6.3, we have also measured (with an appropriate MWPC system, 2 mm wire spacing) the spatial resolution along the z-axis of the counter, obtainable by the time difference between the two PMs H_A and H_B .

Figure 9 shows the correlation between $\Delta t = (t_{H_B} - t_{H_A})$ and the z-coordinate of the impact point of the particle on the counter, as measured by the MWPCs. From the plot we can obtain for the spatial resolution the value $\sigma_z = 2.0$ cm, constant along the whole counter. Since the resolution depends on the difference of the threshold crossing times, it is unaffected by PH correction. The effective

value of the light speed v_e through the counter, averaged over all the possible light trajectories, turns out to be 16 cm/ns (while the light velocity is 19 cm/ns).

7. CONCLUSIONS

Following the suggestions of the light-collection efficiency Monte Carlo calculations, and applying standard PH corrections, we have achieved very high resolutions in TOF measurements performed with "large" scintillation counters. These good performances have been confirmed during the running of PS159 (ref. 1) on a long-term basis and at high intensity; they have proved to be quite stable.

As foreseen by the Monte Carlo, in these test measurements we have obtained much better resolutions with twisted-type light-guides than with fish-tail ones. On the other hand, the results obtained using the PILOT U as plastic scintillator for the large counters, are not very much better than those obtained with NE114, as would be suggested by a theoretical evaluation.

In conclusion, table 6 compares the results we have obtained with the various tested counters, and the results published to date by several authors^{3,5-20}); the data are subdivided into very small (≤ 3 cm), small (≤ 25 cm), and large counters.

APPENDIX

This appendix is concerned with theoretical calculations performed using the CERN Monte Carlo program GUIDE 11 (ref. 2) on the light-collection efficiency, and the shape of the light pulse which reaches the photocathode of a PM, in different types of scintillation counters. Here we briefly summarize results of general interest for the design of counters to be used in high-resolution TOF measurements.

In order to collect the light produced in a scintillator $75 \times 25 \times 2.5 \text{ cm}^3$, we have considered three types of light-guide, each of different dimensions and each with different outside wrapping surfaces. Figure A.1 shows the geometry of the light-guides we have studied: the mechanically simple rectangular one (RT); the trapezoidal "fish-tail" one (FT); the more complex "twisted" guide (TW). The latter consists of an appropriate number of elements in order to transform the rectangular transverse area of the scintillator into a nearly square surface, followed by a properly cut frustum. For PM assembling purposes, all guides are terminated by a plexiglas cylinder (8 cm long, 4 cm $\varnothing$).

In order to study the geometrical characteristics of the different counters, we have considered the scintillator as "ideal" in Sections A.1, A.2, and A.3. That is, the scintillator is assumed to emit a $\delta(t)$ of light with rise-time ρ = decay time τ = 0, and to have zero absorption (attenuation length $\lambda = \infty$). In Section A.4 we have compared the response of two scintillators having the physical properties of the NE114 and the PILOT U (see table 1).

For convenience, and unless otherwise stated, in the following we report results referring to the light collected by one PM only; while in reality, for this type of measurement, the light has to be collected at both ends of the counter (see fig. 1).

The MC results, for each configuration, were obtained using 20,000 emitted photons. Therefore the percentage error of all the quoted efficiencies is $\sigma_{\epsilon}/\epsilon \approx 0.007/\sqrt{\epsilon}$.

A.1 Dimensions of the light-guides

As discussed in Section 2, for high-resolution TOF measurements the length of the guide must be such as to provide the largest light-collection efficiency ϵ ; in particular this applies to the efficiency ϵ_F for "fast" photons collected in the first instants of the light pulse. Furthermore, in order to have a time resolution that is reasonably uniform throughout the counter, ϵ_F must be rather independent of the incident position on the scintillator (see Section 2 for further details).

A.1.1 Fish-tail guides. The FT guide behaviour has been studied as a function of the length ℓ of the trapezoidal tail, considering an "ideal" scintillator $75 \times 25 \times 2.5 \text{ cm}^3$. As an example, fig. A.2 shows the time distribution of the photons reaching the photocathode, with FT guides 10 cm, 40 cm, and 60 cm long, and for a $\delta(t)$ of light generated in three different points of the counter (respectively at 1 cm, NEAR POINT; 37.5 cm, CENTRAL POINT; and 75 cm, FAR POINT, from the edge of the scintillator on the PM side). The short guides have a better total light-collection efficiency ϵ_T , but the efficiency ϵ_F for "fast" photons depends strongly on the particle impact point, thus giving a poor resolution uniformity throughout the counter. If the length ℓ is increased, this non-uniformity decreases, but so does the efficiency. A reasonable compromise is obtained in our case for $\ell = 40 \text{ cm}$, and this is referred to as the "standard" dimension for the FT guide in the following.

It should be noticed that further MC calculations referring to 20 cm large counters, instead of the considered 25 cm, show no substantial advantages.

A.1.2 Twisted guides. For the TW guide, the number of strips is determined by the requirement of matching the rectangular $25 \times 2.5 \text{ cm}^2$ transverse area of the scintillator to an approximately square surface. With three strips we have a surface of $8.3 \times 7.5 \text{ cm}^2$. For good efficiency the strips should not be too long, but long enough, however, to approach the condition of the "ideal" twisted guide. The ideal TW guide would have 100% geometrical light transmission with respect to

a straight guide. In practice the actual value of the light transmission depends on the ratio of the twisting curvature radius R and the width w of the strip along the radius. Using three elements 50 cm long (referred to as the TW standard length in the following), $R \sim 80$ cm and $w = 8.3$ cm; thus $R/w \gtrsim 9$, which corresponds [according to Massam²¹⁾] to a geometrical transmission coefficient $\gtrsim 95\%$ relative to a straight guide. For the sake of simplicity, the MC calculations have been done considering the twisted guides as "ideal".

The aperture angle of the cone joining the strips to the final cylinder has been chosen with the same criteria as those used to determine the FT guide length; 15 cm turned out to be the optimal length to be used for the frustum.

As a final remark, the MC results demonstrate that the use of the connection frustum produces a uniform distribution of photons on the surface of the photocathode, regardless of which strip the light has passed through.

A.1.3 Rectangular guides. From the point of view of "fast" photon collection as a function of the guide length ℓ , the rectangular guides behave, in practice, like the FT ones. The optimum condition is obtained for $\ell = 40$ cm.

A.2 Study of the effect of different outside wrapping surfaces

We have already remarked in Section 2 that only the "fast" photons are the useful ones for high-resolution time measurements; the "slow" photons have a disturbing effect on the correction procedures.

With this in mind we have studied, for an "ideal" scintillator $75 \times 25 \times 2.5$ cm³, the optimum conditions with regard to the external wrapping surface characteristics (absorbing or reflecting). As an example, in our calculations we have assumed for an external mirror surface a reflection coefficient of 98%.

Using a standard length FT guide, we obtain the following results. With no reflecting outside surface, ϵ_T for a particle crossing the "ideal" scintillator 123 cm away from the photocathode (FAR point) is 2.7%. If the final cylinder is "aluminized" (i.e. externally wrapped by a mirror surface), the efficiency increases to $\epsilon_T = 3.3\%$. "Aluminizing" also the trapezoidal tail, ϵ_T becomes slightly

higher, at 3.4%. Finally, if the whole counter is "aluminized", the small increase in ϵ_T is due only to the collection of "slow" photons, which have suffered many reflections. This gives no improvement to the pulse rise-time.

Similar results were obtained for the TW guides. In the "standard" geometry conditions (three elements of 50 cm, and a frustum 15 cm long connected to the final cylinder), "aluminizing" the final cylinder gives ϵ_T for FAR point increased from 4.0% (corresponding to external absorbing surfaces for the whole counter) to 4.7%. If the frustum also is "aluminized", $\epsilon_T = 5.3\%$. No improvement in the collection of the "fast" photons is achieved if also the twisted strips or the whole counter are wrapped with reflecting surfaces.

In the RT guide case, from the point of view of the fast response of the counter, it is only necessary to "aluminize" the final cylinder.

For these reasons we will assume the following conditions as being "standard" for the outside wrapping surfaces. All counters are externally wrapped with absorbing black paper except for the final part of the light-guides. The final cylinder must be "aluminized" in all cases; in addition, the trapezoidal tail of the FT guide, and the conical frustum in the TW case, must also be "aluminized" (see fig. A.1).

A.3 Comparison between different types of light-guide

Considering once more an "ideal" scintillator [i.e. emitting a $\delta(t)$ light pulse and having $\lambda = \infty$], with "standard" geometrical conditions and outside surfaces as defined in the previous sections, we have computed the geometrical light-collection efficiency for counters with the three different types of light-guide.

Figure A.3 shows the dependence of the efficiency for the total light-collection ϵ_T and of the "fast" photon efficiency ϵ_F (0.6 ns) (i.e. collected in the first 0.6 ns) as a function of the distance z between the photocathode and the particle impact point. At the CENTRAL point the total collection efficiency is $\epsilon_T = 5.5\%$ for the TW guide, $\epsilon_T = 3.8\%$ for the RT guide, and $\epsilon_T = 3.1\%$ in the FT guide case. In all cases an over-all efficiency of $2 \times \epsilon_T$ is obtained if the

light is collected at both ends of the counter. The collection efficiency for "fast" photons ϵ_F (0.6 ns) is 2.1% for the TW guide (38% of the total collected light), 1.0% for the FT (32% of the total), and 0.8% in the RT guide case (21% of the total): FT is better than RT in this case, because the RT guide collects a large number of "slow" photons. This can clearly be seen in fig. A.4, where the time distribution of the photons collected at the photocathode is shown for a particle crossing the centre of the scintillator connected to the TW, RT, and FT guides.

From these results, the TW guides appear to be the best for obtaining a large fast response from a counter to be used in high-resolution time measurements. The FT guides are in turn more appropriate than the RT ones. Thus we have rejected the RT guide counters, and all further analysis is devoted to TW and FT comparison.

A map of the efficiency as a function of the emitting position throughout the whole counter gives values largely contained within the limits shown in fig. A.3. In fact, fig. A.3 corresponds to the positions of maximum non-uniformity.

A.4 Comparison between counters using FT and TW light-guides and NE114 and PILOT U as scintillator

To obtain a more significant comparison between the response of the counters considered, we have introduced into the MC program the rise-time ρ , decay time τ , and attenuation length λ for the two different plastic scintillators: the NE114 and the PILOT U (see table 1).

The results refer, as usual, to a $75 \times 25 \times 2.5 \text{ cm}^3$ scintillator connected to TW and FT light-guides having "standard" geometries and "standard" outside surface conditions, as previously defined.

Figure A.5 shows how the NE114 counters, because of the large value of the attenuation length λ , exhibit an ϵ_T higher than that of the corresponding PILOT U counters. On the other hand, the light collection in the first nanosecond, ϵ_F (1.0 ns), is clearly better for the PILOT U counters, since they have a much faster light response. Furthermore, we can see that the TW guides, independent of the

type of scintillator used, allow a light collection superior to that obtainable with the corresponding FT guides.

If we also take into account the different light-conversion efficiency of the two types of scintillator, then the situation is completely in favour of the PILOT U counters. This is clearly visible in fig. A.6, where the time distribution of the photons collected at the photocathode is shown for all four cases with a minimum ionizing particle crossing the centre of the scintillator.

Finally, fig. A.7 shows the shape of the voltage pulse $V(t)$ to be expected at the anode of a fast PM: the NE114 and PILOT U scintillators are connected to the "standard" TW guide, and the light is generated by a minimum ionizing particle incident on the centre of the counter. The $V(t)$ were computed by folding the light pulse at the photocathode with the time distribution generated by a PM XP2020. We have assumed the over-all response of the PM to be equal to the current pulse shape due to a single photoelectron²²); this appears to be a very good approximation.

Also in fig. A.7 we report measurements, for the NE114 counter, made on the rising part of the pulse by determining the output time displacements corresponding to threshold variations of the LOW discriminators (see Section 3). The experimental results agree quite well with the calculated voltage pulse.

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Table 1

Physical characteristics of the scintillators⁴⁾ considered

Type of scintillator	NE114	PILOT U
Decay-time (short component), τ	4.0 ns	1.36 ns
Rise-time, ρ	~ 1.0 ns	0.5 ns
Light attenuation length (1/e), λ	3.5-4.0 m	1.4 m
Light output relative to anthracene	42%	67%
Wavelength of maximum emission	4340 Å	3910 Å
Density (g/cm ³)	1.032	1.032
Atomic ratio, H/C	1.109	1.100
Refractive index, n	1.58	1.58

Table 2

Standard deviations obtained for the uncorrected and corrected TOF distributions with small-area counters; $\sigma_{\text{intr}}(S_j)$ is the contribution of the single S_j counter. The statistical error is $\sim 1\%$.

Counters S_1 and S_2			$\left\{ \begin{array}{l} \sigma(S_2 - S_1) \\ \sigma_{\text{intr}}(S_j) \end{array} \right\}$	$\left\{ \begin{array}{l} \sigma(\overline{S_2} - \overline{S_1}) \\ \sigma_{\text{intr}}(\overline{S_j}) \end{array} \right\}$	$\left\{ \begin{array}{l} \sigma(\overline{S_2} - \overline{\overline{S_1}}) \\ \sigma_{\text{intr}}(\overline{\overline{S_j}}) \end{array} \right\}$
Scintillator	Area (cm ²)	Thickness (cm)	(ns)	(ns)	(ns)
NE114	10 × 5	2	$\left\{ \begin{array}{l} 0.18 \\ 0.13 \end{array} \right\}$	$\left\{ \begin{array}{l} 0.083 \\ 0.059 \end{array} \right\}$	$\left\{ \begin{array}{l} 0.081 \\ 0.056 \end{array} \right\}$
PILOT U	10 × 5	1	$\left\{ \begin{array}{l} 0.20 \\ 0.14 \end{array} \right\}$	$\left\{ \begin{array}{l} 0.11 \\ 0.078 \end{array} \right\}$	

Table 3

Comparison between the TOF resolutions obtained with different types of light-guide (FT and TW) connected to the same NE114 scintillator, $100 \times 15 \times 3 \text{ cm}^3$. Uncorrected and corrected standard deviations, as well as the contributions of the H counter, are listed. Particles are impinging on either the centre or the edge of the scintillator. The statistical errors are $\sim 1-2\%$.

START - Counter S: NE114 scintillator $10 \times 5 \times 2 \text{ cm}^3$ STOP - Counter H: NE114 scintillator $100 \times 15 \times 3 \text{ cm}^3$						
Light-guides of the H counter	Central position			Edge position		
	$\left\{ \begin{array}{l} \sigma(\text{H-S}) \\ \sigma_{\text{intr}}^{(\text{H})} \end{array} \right.$ (ns)	$\left\{ \begin{array}{l} \sigma(\bar{\text{H}}-\bar{\text{S}}) \\ \sigma_{\text{intr}}^{(\bar{\text{H}})} \end{array} \right.$ (ns)	$\left\{ \begin{array}{l} \sigma(\text{H}^*-\bar{\text{S}}) \\ \sigma_{\text{intr}}^{(\text{H}^*)} \end{array} \right.$ (ns)	$\left\{ \begin{array}{l} \sigma(\text{H-S}) \\ \sigma_{\text{intr}}^{(\text{H})} \end{array} \right.$ (ns)	$\left\{ \begin{array}{l} \sigma(\bar{\text{H}}-\bar{\text{S}}) \\ \sigma_{\text{intr}}^{(\bar{\text{H}})} \end{array} \right.$ (ns)	$\left\{ \begin{array}{l} \sigma(\text{H}^*-\bar{\text{S}}) \\ \sigma_{\text{intr}}^{(\text{H}^*)} \end{array} \right.$ (ns)
Fish-tail (FT) 40 cm long	$\left\{ \begin{array}{l} 0.25 \\ 0.22 \end{array} \right.$	$\left\{ \begin{array}{l} 0.19 \\ 0.18 \end{array} \right.$	$\left\{ \begin{array}{l} 0.19 \\ 0.18 \end{array} \right.$	$\left\{ \begin{array}{l} 0.22 \\ 0.19 \end{array} \right.$	$\left\{ \begin{array}{l} 0.14 \\ 0.13 \end{array} \right.$	$\left\{ \begin{array}{l} 0.13 \\ 0.12 \end{array} \right.$
Twisted (TW) two strips 40 cm long + 15 cm frustum	$\left\{ \begin{array}{l} 0.27 \\ 0.23 \end{array} \right.$	$\left\{ \begin{array}{l} 0.13 \\ 0.12 \end{array} \right.$				

Table 4

Uncorrected and corrected TOF resolutions obtained with an NE114 scintillator, $75 \times 25 \times 3 \text{ cm}^3$, connected to twisted-type light-guides; $\sigma_{\text{intr}}^{(\text{H})}$ is the contribution of the H counter. Particles are crossing the centre of the counter. The statistical errors are 1-2%.

START - Counter S: NE114 $10 \times 5 \times 2 \text{ cm}^3$ STOP - Counter H: NE114 $75 \times 25 \times 3 \text{ cm}^3$		
Light-guides of the H counter	Central position	
	$\left\{ \begin{array}{l} \sigma(\text{H-S}) \\ \sigma_{\text{intr}}^{(\text{H})} \end{array} \right.$ (ns)	$\left\{ \begin{array}{l} \sigma(\bar{\text{H}}-\bar{\text{S}}) \\ \sigma_{\text{intr}}^{(\bar{\text{H}})} \end{array} \right.$ (ns)
Twisted (TW) three strips 50 cm long + 15 cm frustum	$\left\{ \begin{array}{l} 0.26 \\ 0.22 \end{array} \right.$	$\left\{ \begin{array}{l} 0.14 \\ 0.13 \end{array} \right.$

Table 5

Uncorrected and corrected TOF resolutions obtained with a PILOT U scintillator, $75 \times 25 \times 2.5 \text{ cm}^3$, connected to twisted-type light-guides; $\sigma_{\text{intr}}(\text{H})$ is the contribution of the H counter. Particles are crossing either the centre or the extreme edge of the scintillator. The statistical errors are $\sim 1\text{-}2\%$.

START - Counter S: PILOT U $10 \times 5 \times 1 \text{ cm}^3$				
STOP - Counter H: PILOT U $75 \times 25 \times 2.5 \text{ cm}^3$				
Light-guides of the H counter	Central position		Edge position	
	$\left\{ \begin{array}{l} \sigma(\text{H-S}) \\ \sigma_{\text{intr}}(\text{H}) \end{array} \right.$ (ns)	$\left\{ \begin{array}{l} \sigma(\bar{\text{H}}-\bar{\text{S}}) \\ \sigma_{\text{intr}}(\bar{\text{H}}) \end{array} \right.$ (ns)	$\left\{ \begin{array}{l} \sigma(\text{H-S}) \\ \sigma_{\text{intr}}(\text{H}) \end{array} \right.$ (ns)	$\left\{ \begin{array}{l} \sigma(\bar{\text{H}}-\bar{\text{S}}) \\ \sigma_{\text{intr}}(\bar{\text{H}}) \end{array} \right.$ (ns)
Twisted (TW) three strips 50 cm long + 15 cm frustum	$\left\{ \begin{array}{l} 0.28 \\ 0.23 \end{array} \right.$	$\left\{ \begin{array}{l} 0.15 \\ 0.13 \end{array} \right.$	$\left\{ \begin{array}{l} 0.29 \\ 0.25 \end{array} \right.$	$\left\{ \begin{array}{l} 0.19 \\ 0.16 \end{array} \right.$

Table 6

Comparison between our results and results published to date by several authors. The data are subdivided into three sections corresponding to very small (≤ 3 cm), small (≤ 25 cm), and large counters. The type of light-guide is indicated in square brackets. Intrinsic time resolutions are indicated by underlining the FWHM values.

Authors	Type of scintillator	Scintillator dimensions (cm ³)	Type of PM	Spatial resolution FWHM (cm)	Time resolution FWHM (ps)
A. Schwarzschild ⁵) (1963)	Naton 136	$\emptyset 1.27 \times 1.27$	56AVP		320
W. Flauger et al. ⁶) (1964)	Naton 136	$\emptyset 2.54 \times 2.54$	56AVP		240
G. Present et al. ⁷) (1964)	Naton 136	$\emptyset 1.9 \times 1.9$	XP1020		210
H. Weisberg ⁸) (1965)	Naton 136	$\emptyset 2.54 \times 2.54$	RCA 7850		225
G. Bertolini et al. ⁹) (1966)	Naton 136	$\emptyset 2.54 \times 2.54$	XP1020		192
J.A. Miehe et al. ¹⁰) (1966)	Naton 136	$\emptyset 2.0 \times 1.0$	RCA C-70045		185
B. Bengtson et al. ¹¹) (1970)	NE111	$\emptyset 2.5 \times 1.0$	XP1021		132
J. Bialkowsky et al. ¹²) (1972)	NE111	$\emptyset 2.5 \times 1.0$	XP1021		130
F. Binon et al. ¹³) (1978)	NE102A	$3.0 \times 1.0 \times 0.4$	XP2020		<u>113</u>
F. Binon et al. ¹³) (1978)	NE102A	$25 \times 2 \times 2$	XP2020		<u>217</u>
This paper	NE114	$10 \times 5 \times 2$ [RT]	XP2020		<u>130</u>
" "	PILOT U	$10 \times 5 \times 1$ [RT]	XP2020		<u>180</u>
G. Charpak et al. ¹⁴) (1962)	Plastic scint.	$40 \times 12 \times 1$ [FT]	56AVP	5	
H. Müller et al. ¹⁵) (1966)	Plastic scint.	$160 \times \emptyset 10$ [cone]	56AVP	2.5	600
D. Bollini et al. ¹⁶) (1969)	Organic scint. with wave-shifter	$100 \times 18 \times 18$ [RT]	56AVP	2.8	700
R.G. Astvatsaturor et al. ¹⁷) (1970)	Plastic scint.	$130 \times 8 \times 8$ [cone]	56AVP	3.4	760
S.A. Buniatov et al. ¹⁸) (1972)	Plastic scint.	$70 \times 10 \times 10$ [cone]	XP1020	2.2	
" " " " "	" "	" " " "	FEU-30	3.0	800
J.T. Dakin ¹⁹) (1974)	PILOT Standard Mineral oil scint.	$305 \times 20 \times 20$ [cone]	56DVP	23.6	1400
G. Feldman ¹⁹) (1974)	Plastic scint.	$254 \times 20 \times 2.5$ [FT]	56DVP	8.0	800
A.N. Khrenov et al. ²⁰) (1974)	Plastic scint.	$120 \times 10 \times 10$ [RT]	XP1020	3.6	560
" " " " "	" "	" " " "	FEU-63	5.3	640
W. Braunschweig et al. ³) (1976)	NE110	$172 \times 20 \times 2$ [TW]	RCA 8575	~ 5	500
This paper	NE114	$100 \times 15 \times 3$ [FT]	XP2020		<u>400</u>
" "	NE114	$100 \times 15 \times 3$ [TW]	XP2020		<u>280</u>
" "	NE114	$75 \times 25 \times 3$ [TW]	XP2020		<u>300</u>
" "	PILOT U	$75 \times 25 \times 2.5$ [TW]	XP2020	4.8	<u>300</u>

Figure captions

- Fig. 1 : Geometry of the scintillation counters: a) small S counter, $10 \times 5 \text{ cm}^2$, with rectangular light-guides; b) counter H, $100 \times 15 \text{ cm}^2$, with fish-tail type light-guides; c) counter H, $100 \times 15 \text{ cm}^2$, with two-twisted-strip light-guides; d) counter H, $75 \times 25 \text{ cm}^2$, with three-twisted-strip light-guides. Surfaces not wrapped with aluminized mylar are covered by absorbing black paper.
- Fig. 2 : Schematic set-up for TOF measurements between two counters, C_1 and C_2 , placed at a distance b . C is a small definition counter. L and H indicate the low- and high-threshold discriminators.
- Fig. 3 : Elimination of "accidental" events.
- a) Plot of the LOW threshold crossing time t_{1A}^L of PM C_{1A} versus the LOW signal t_{1B}^L of the PM C_{1B} . The starting time of the TDC is driven by the HIGH threshold crossing time t_{1A}^H of the PM C_{1A} ; physically "good" events are confined within the circle;
- b) Plot of t_{1A}^H versus t_{1A}^L : "good" events lie inside the 45° band.
- Fig. 4 : TOF distributions obtained with small-area S counters $\sim 7.5 \text{ m}$ apart. No definition counter was used, therefore the beam illuminated the whole of each scintillator.
- a) NE114 scintillators: — uncorrected TOF ($\sigma = 0.18 \text{ ns}$, $\Delta T_{5\%} = 0.95 \text{ ns}$); --- TOF after PH correction ($\sigma = 0.083 \text{ ns}$, $\Delta T_{5\%} = 0.40 \text{ ns}$);
- b) PILOT U scintillators: — uncorrected TOF ($\sigma = 0.20 \text{ ns}$, $\Delta T_{5\%} = 0.90 \text{ ns}$); --- PH-corrected TOF ($\sigma = 0.11 \text{ ns}$, $\Delta T_{5\%} = 0.55 \text{ ns}$).
- Fig. 5 : Plots of the PH, $A\check{C}_0$, of an aerogel Čerenkov counter $\check{C}_0$ (refractive index $n = 1.05$) versus the uncorrected (a) and PH-corrected (b) TOF measured, without any definition counter, between the two $10 \times 5 \text{ cm}^2$ PILOT U counters, 1 cm thick. The beam momentum was $1.4 \text{ GeV}/c$.

Fig. 6 : TOF distributions obtained between a $10 \times 5 \times 2 \text{ cm}^3$ NE114 scintillation counter S and an NE114 scintillator H, $100 \times 15 \times 3 \text{ cm}^3$, connected to two-twisted-element light-guides. The 1.4 GeV/c particles are crossing the centre of the H counter.

— Uncorrected TOF ($\sigma = 0.27 \text{ ns}$, $\Delta T_{5\%} = 1.4 \text{ ns}$);

--- PH-corrected TOF ($\sigma = 0.13 \text{ ns}$, $\Delta T_{5\%} = 0.65 \text{ ns}$).

Fig. 7 : TOF distributions obtained between a $10 \times 5 \times 2 \text{ cm}^3$ NE114 scintillation counter S and an NE114 scintillator H, $75 \times 25 \times 3 \text{ cm}^3$, connected to three-twisted-element light-guides. The 1.4 GeV/c particles are crossing the centre of the H counter.

— Uncorrected TOF ($\sigma = 0.26 \text{ ns}$, $\Delta T_{5\%} = 1.3 \text{ ns}$);

--- PH-corrected TOF ($\sigma = 0.14 \text{ ns}$, $\Delta T_{5\%} = 0.80 \text{ ns}$).

Fig. 8 : TOF separation of 1.4 GeV/c π 's and K's obtained with a $10 \times 5 \times 1 \text{ cm}^3$ PILOT U scintillation counter S and a PILOT U scintillator H, $75 \times 25 \times 2.5 \text{ cm}^3$, connected to three-twisted-element light-guides. The distance between the counters is $\sim 5.5 \text{ m}$, and the 1.4 GeV/c particles hit the H counter in the centre.

— Uncorrected TOF ($\sigma = 0.28 \text{ ns}$, $\Delta T_{5\%} = 1.25 \text{ ns}$);

--- PH-corrected TOF ($\sigma = 0.15 \text{ ns}$, $\Delta T_{5\%} = 0.65 \text{ ns}$).

Fig. 9 : Correlation between the difference of the two LOW threshold crossing times $\Delta t = t_{H_B} - t_{H_A}$ and the z-coordinate of the incident particle, as measured by a system of MWPCs. The H counter consists of a $75 \times 25 \times 2.5 \text{ cm}^3$ PILOT U scintillator connected to three twisted elements 50 cm long. The spatial resolution $\sigma_z = 2.0 \text{ cm}$ is constant throughout the whole counter.

Fig. A.1 : Geometry of the light-guides considered in the MC calculations.

Fig. A.2 : Time distribution of the photons collected at the photocathode of one PM by FT guides 10 cm, 40 cm, and 60 cm long. The light is generated by an "ideal" scintillator, $75 \times 25 \times 2.5 \text{ cm}^3$ [$\delta(t)$ light pulse, $\lambda = \infty$] in three different points, at 1 cm, 37.5 cm, and 75 cm from the edge of the scintillator.

Fig. A.3 : Total light-collection efficiencies ϵ_T , and efficiencies ϵ_F (0.6 ns) for "fast" photons reaching the PM within the first 0.6 ns, as a function of the distance z between the photocathode and the point where the light is generated. The $75 \times 25 \times 2.5 \text{ cm}^3$ scintillator is considered as "ideal" [$\delta(t)$ light pulse, $\lambda = \infty$]. The results for three different types of light-guides (RT, FT, and TW) are compared.

Fig. A.4 : Time dependence of the light-collection efficiencies for a $75 \times 25 \times 2.5 \text{ cm}^3$ scintillator, connected to three different types of light-guides, RT, FT, and TW, having the geometries shown in fig. A.3. The light is generated in the centre of the scintillator, considered as "ideal" [$\delta(t)$ light pulse, $\lambda = \infty$].

Fig. A.5 : Light-collection efficiencies as a function of the distance z between the photocathode and the impact point of the particles on the $75 \times 25 \times 2.5 \text{ cm}^3$ scintillator. Two different types of scintillator, NE114 and PILOT U, are connected to FT and TW light-guides, having the geometries shown in fig. A.3.

a) Total light collection efficiencies $\hat{\epsilon}_T$.

b) Collection efficiencies ϵ_F (1.0 ns) within the first 1.0 ns.

Fig. A.6 : Time distributions of the photons collected at the photocathode of one PM by two different light-guides, FT and TW, connected to different types of plastic scintillator: the NE114 and the PILOT U. The light is generated by a minimum ionizing particle crossing the centre of the $75 \times 25 \times 2.5 \text{ cm}^3$ scintillator.

Fig. A.7 : Shapes of the output voltage pulse $V(t)$ to be expected at the anode of a Philips XP2020 photomultiplier. The NE114 and PILOT U $75 \times 25 \times 2.5 \text{ cm}^3$ scintillators are connected to a TW guide, having the geometry shown in fig. A.6. The light is generated by a minimum ionizing particle crossing the centre of the counter. The experimental points are normalized to the calculated curve on the basis of the peak values.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Plexiglas
 Aluminized mylar

Fig. A.1

Fig. A.2

Fig. A.3

Fig. A.4

Fig. A.5

Fig. A.6

Fig. A.7