PHYSICAL PROPERTIES OF THE TOF (TIME OF FLIGHT) SCINTILLATION COUNTERS OF DELPHI

**J.M. Benlloch, M.V. Castillo, A. Ferrer, J. Fuster, E. Higon,
A. Llopis, J. Salt, E. Sanchez, E. Sanchis, E. Silvestre**
I.F.I.C., Instituto de Fisica Corpuscular
Centro Mixto Universitat de Valencia – Consejo Superior de Investigaciones Cientificas

J. Cuevas
Departamento de Fisica Moderna, Universidad de Cantabria

PHYSICAL PROPERTIES OF THE TOF (TIME OF FLIGHT) SCINTILLATION COUNTERS OF DELPHI

J.M. Benlloch, M.V. Castillo, A. Ferrer, J. Fuster, E.Higón,

A. Llopis, J. Salt, E. Sánchez, E. Sanchis, E. Silvestre

I.F.I.C., Instituto de Física Corpuscular

Centro Mixto Universitat de València - Consejo Superior de Investigaciones Científicas

J. Cuevas

Departamento de Física Moderna, Universidad de Cantabria.

November 8, 1989

Abstract: In this paper we report the physical properties of the Time of Flight scintillator counters used for Delphi Experiment at CERN. We discuss in this paper the different choices studied for the wrapping of the counters in order to obtain best efficiencies for light transmission. A very good agreement of the performances of the counters has been found with the results of an original Monte-Carlo program. The main characteristics of the TOF counters of Delphi are: an effective light attenuation length of 135 cm, effective light speed of 15.91 cm/ns, a time resolution of 1.2 ns., and an efficiency for detection of minimum ionizing particles of 99.9%.

1.- INTRODUCTION.

In DELPHI, one of the four LEP (Large Electron Positron collider) experiments at CERN, a TOF (time of flight detector) has been implemented, with the following main objectives [1]:

- 1) To provide a good timing signal derived from cosmic muons (Cosmic Trigger). These cosmic particles will be used to calibrate and to align other detectors from DELPHI.
- 2) To provide a fast signal easily incorporated into the first and second level trigger.
- 3) To digitize the time of flight for charged particles originated from the LEP collisions (this information will be used in the third level trigger of the experiment).
- 4) To estimate the total energy deposited in the TOF detector by charged particles.

For this purpose we have designed a system of 172 scintillator counters ($350 \times 19 \times 2 \text{ cm}^3$) distributed with axial symmetry in the DELPHI barrel region. The counters have been placed at a distance of 3.1 m from the beam pipe and have a length of 7 m [2], [3], [4], [5] subtending angles from the interaction point in between 38° and 142° in theta.

In this paper we report the physical properties of the scintillators used, whose geometry will be described in detail in section 2. The study has been carried out using cosmic radiation and also a N_2 laser, injecting light pulses into the detector using optical fibers: the set-up will be described in section 3. The detector simulation is explained in section 4. In section 5 we will study the light collection efficiency. Results on the absolute attenuation length of 168 cm in the scintillator have been obtained, the effective light speed found in the scintillator is 15.91 cm/ns , will be stated in section 6. In section 7 we will pay special attention to the Cerenkov effect which takes place in the optical guide and influences on the time of flight measurements. In the last section we report on the results about temporal and spatial resolutions in the counter.

2.- COUNTER DESIGN.

The scintillator material used in the TOF is NE110: the technical data appear in table 1. The light is detected by two EMI 9902KB photomultipliers (PMs): these PMs have a 39 mm. diameter and a ten-stage dynode chain. They have antimoniated first dynodes (the material is CsSb) with a high secondary emission ratio, that reduces the PM time jitter and increases the gain. In the voltage dividers used by us some changes have been carried

out on the schemes provided by the manufacturers, in order to get a better shape of the output signal. The reader can find a complete study of the PMs and dividers in [6].

Two curved light guides made of plexiglass carry the light from the scintillator to the PMs. In figure 1 we can see the geometry of the scintillator counters. The geometrical design of the light guides is quite uncommon in TOF detectors due to the bend of 180° of the photons optical path. This requirement was necessary in order to avoid the foreseen magnetic field close to the DELPHI iron yoke. This geometry generates a problem due to the time of flight measurements being masked by Cerenkov's light produced when particles cross over a light guide and the scintillator. This problem will be treated later.

The light guides and the scintillator were glued together with optical cement type NE 581. In order to get a good contact between guides and PMs we have used optical grease.

The scintillator was covered with thin reflecting aluminum foils to get a better efficiency. We have considered several different types of covers in the guides and chosen those that give the best efficiency.

3.- SET UP DESCRIPTION.

3.1. The laser set-up.

We used a N_2 laser to measure the light attenuation length and the effective light speed in the scintillator. The laser characteristics are shown in table 2.

Figure 2 shows the arrangement of the measurement system. The laser light was fed to two PHILIPS 2020 PMs by means of two silicon optical fibres whose characteristics appear in table 3. The coincidence of both discriminated signals provided the trigger. The start signal for the TDC (LECROY 2228 A) and the ADC (LECROY 2249 A) gate came from the trigger. By other similar optical fibers we conducted the laser light to the scintillator under study, where it was connected to one coupling prism (see fig. 3) The light was injected into the fibers by direct exposition to the laser beam. The exit signals from the PMs were splitted as follows: 25 % was digitized by the ADC and 75 % triggered the leading edge discriminator which output stopped the TDC.

3.1. The cosmic set-up.

A part of the test was performed with cosmic radiation at the laboratory. In figure 1 we can see the arrangement of the counters. The cosmic particle was defined by two trigger counters S1 and S2 with a cross section of $6 \times 20 \text{ cm}^2$ and 1 cm thick each one, viewed by an EMI 9903 PM. The coincidence of the two discriminated signals from S1 and S2 gave the trigger.

By moving S1 and S2 we can select different impact points and incidence angles in the scintillator as well as in the guides.

4.- DETECTOR SIMULATION.

Most programs which make the tracking of the photons define all the surfaces of the light guides and calculate the intersection of the straight line of the trajectory with those surfaces. Each time the photon bounces, the new direction is computed and the next intersection point is calculated. If the photon bounces many times this procedure is very time consuming.

We have developed a fast Monte-Carlo program to simulate the detector. Our method has been to divide the counter into volumes with simple geometrical shapes and to define the surfaces of entrance and exit in each of them. Given the position and direction at the entrance, the position and direction at the exit is obtained by simple formulae. The idea is to split the track of a photon into its projections in the YZ and XZ planes, Z being the interesting direction in the volume.

For instance, for the scintillator, which is a parallelepipedic volume, the formulae are:

a) Distance travelled in XZ projection:

$$DX = \frac{L_Z * CXP}{CZP}$$

where CXP,CYP,CZP are the cosinus of the angles of emission of the photon and L_Z the length of the parallelepiped.

b) Number of bounces in that projection:

$$NX = INT\left(\frac{|DX| + \frac{L_X}{2} + \sigma(DX) X}{L_X}\right)$$

where X is the x coordinate value.

c) Final X position and director cosinus are:

$$XP = \sigma(DX) (-)^{NX} * (|DX| + \sigma(DX) X - L_X NX)$$

$$CXP' = CXP (-1)^{NX}$$

Analog expresions apply in the YZ plane.

The total length travelled by a photon is the length in the Z-direction divided by the Z direction cosinus, assumming perfect reflections on the walls:

$$PL = \frac{L_Z}{CZP}$$

Then the probability of the photon to arrive at the end is calculated on this basis:

$$Prob = (-1)^{NX} e^{\frac{PL}{\lambda}}$$

A detailed description of the Monte-Carlo is given in [7]. Comparison with real data will be shown in the following sections.

5.- EFFICIENCY OF THE BENT AND STRAIGHT GUIDES WRAPPING.

It is well known that the efficiency of TOF counters strongly depends on the optical guides wrapping. In order to improve the temporal resolution in TOF measurements, counters have absorbing external surfaces to collect only fast photons that arrive at the photocathode by total reflexion [8]. In our case, due to the large scintillator area and to the losses in the guides (see table 5), it is very important to carry the maximum number of photons to the PM and, Montecarlo calculations show that for better detection efficiency the guides should have reflecting external surfaces.

Different measurements have been made in order to obtain the best wrapping for the bent and straight light guides. Several aluminated papers and some mirrorlike surfaces (by deposition of aluminum in vacuum) have been tested. We have measured the reflexion coefficient R for each configuration: the highest value corresponds to the plastic covered with aluminated paper $R_1 = 0.86$. With deposition of aluminum one obtains $R_2 = 0.75$. With a double deposition, the reflexion coefficient is always a quite below the simple vacuum deposition ($R_3 = 0.60$): it seems as if the process produces some damage to the cylinder surface.

We have measured the efficiencies versus the discrimination threshold in the center of the counter and near the scintillator end (see fig. 4).

We conclude from these curves that a good efficiency is obtained with the guide covered with aluminated paper. This is the most efficient in agreement with the correlated reflexion indices.

The efficiency curve in the center for a typical counter with the guide covered with aluminated paper is shown in figure 5 as well as the equivalent number of photoelectrons for the threshold voltages . The most striking result is that in the scintillator ends the efficiency is 100% at -75 mV of discrimination level, for minimum ionizing particles (cosmic muons).

6.- MEASUREMENT OF THE ATTENUATION LENGTH AND EFFECTIVE SPEED OF LIGHT.

In order to determine the attenuation length and effective speed of the light in the detectors, we have carried out different tests using cosmic radiation and laser light injection.

The determination of the attenuation length is based on the measurement of the charge Q deposited in the ADCs, while the effective speed of light is based on the arrival time of the signal to the TDCs.

The measurements are performed at several points Z_i of the detector. If an exponential decrease of the signal is supposed to be valid, we will have

$$Q_{Z_i} = N e^{\frac{-(l_c - Z_i)}{\lambda}} \quad (1)$$

where Q_{Z_i} stands for the mean value of the ADC at point Z_i .

N is a constant including the number of produced photons, efficiency factors in the light guides, quantum efficiency, etc.

l_c is the length of the detector

λ is the attenuation length to be determined

Taking as Q_{Z_o} the mean value of the ADC in one end of the scintillator ($Z_o = 0$) we will get

$$\ln \frac{Q_{Z_i}}{Q_{Z_o}} = \frac{Z_i}{\lambda} \quad (2)$$

which allows us to determine the attenuation length by a linear fit.

On the other hand

$$V_{ef} = \frac{l_c - Z_i}{t_i} \quad (3)$$

where V_{ef} is the effective speed of the light inside the scintillator and t_i the time recorded for each position.

Calculations have been made only with minimum ionizing particles (mips) hitting the detector at right angles: for this purpose we have rejected those events for which their ADC value differs more than 2σ from the most probable value of the distribution.

The values of λ obtained with cosmic and laser radiation are compatible. they are :

$$\lambda_{laser} = 135 \pm 10 \text{ cm} \quad \lambda_{cosm.} = 140 \pm 15 \text{ cm}$$

We show in figure 6 the fitted curve for the determination of λ_{laser}

Another way to determine the attenuation length is to use in expressions (1) and (2) the most probable value instead of the mean value of the distribution. We have got similar λ values with this method.

The obtained value for the effective speed is

$$V_{ef} = 15.91 \pm 0.14 \text{ cm/ns}$$

and the fit can be seen in fig. 7.

Note that the real speed of the light inside the scintillator is $V = c/n$, being n the refraction index, so the actual length l traversed by the photons is $l = \frac{c}{V_{ef} * n} * l_{ef}$ and we have to regard the measured attenuation length as an effective value in our counter, related to the absolute attenuation length of the NE110 material by the factor $\frac{c}{V_{ef} * n}$. So the absolute attenuation length is $\lambda = 168 \pm 15 \text{ cm}$

7.- CERENKOV LIGHT PRODUCED IN THE OPTIC GUIDES.

Due to the peculiar design of the Delphi TOF counters, 32% of the detector surface is covered by the light guide, so that when a particle hits both elements, two different processes contribute in the global light production: scintillation in the counter and Cerenkov effect in the guide [9], [10].

The number of scintillation photons is several orders of magnitude higher than the Cerenkov one; however, due to the large size of the scintillator and to the attenuation of the signal, we have to use low discrimination levels in order to get 100% efficiency. Then, it might happen that the Cerenkov signal exceeds the threshold voltage and sets in advance the stop of the TDC. It is not possible either to eliminate the Cerenkov radiation by means of filters put at the end of the guides, because the wave length of both radiations is similar.

Let us see now the consequences of this effect in the time of flight measurements : suppose that a particle hits the counter in x_1 (see fig. 1), and that the start signal of the TDCs is referred to the point $y=A$. The output signals of the PMs stop the TDC. The measured times will be :

$$t_1 = \tau + \frac{l_c/2 - x_1}{v_1} + \frac{l_g}{v_2} + t_{01} \quad (4)$$

$$t_2 = \tau + \frac{l_c/2 + x_1}{v_1} + \frac{l_g}{v_2} + t_{02} \quad (5)$$

Where τ is the particle time of flight, l_c and l_g the lengths of the counter and guide, v_1 and v_2 the effective speeds of the scintillation light in the scintillator and guides, and t_{01} and t_{02} are temporal constants associated with the photomultiplier's transit time and the cable length.

From (4) and (5) and supposing that $t_{01} = t_{02} = 0$:

$$x_1 = \frac{v_1(t_2 - t_1)}{2} \quad (6)$$

$$\tau = \frac{t_2 + t_1}{2} - \frac{l_c}{2v_1} - \frac{l_g}{v_2} \quad (7)$$

If the particle hits the counter in x_2 and the Cerenkov radiation gives the TDC stop, t_1 and t_2 will be :

$$t_1 = \tau + \frac{l_g - (l_c/2 - x_2)}{v_3} \quad (8)$$

$$t_2 = \tau + \frac{l_c/2 + x_2}{v_1} + \frac{l_g}{v_2} \quad (9)$$

being v_3 the effective speed of the Cerenkov light in the guide. This speed is not constant, it depends on the incidence angle of the particle in the guide because the Cerenkov radiation is directed with emission angle :

$$\theta = \arccos\left[\frac{1}{n * \beta}\right]$$

In this case the expresions for x_2 and τ are much more complicated :

$$x_2 = \frac{(t_2 - t_1) + \frac{l_g - l_c/2}{v_3} - \frac{l_c/2}{v_1} - \frac{l_g}{v_2}}{\frac{1}{v_1} - \frac{1}{v_3}} \quad (10)$$

$$\tau = \left(1 - \frac{v_3}{v_3 - v_1}\right)t_2 + \frac{v_3}{v_3 - v_1}t_1 - \frac{1}{v_3 - v_1}[l_g(1 - \frac{v_1}{v_2}) - l_c] \quad (11)$$

The efficiency of our TOF does not decrease because of this effect, and the temporal error will be corrected 'off line'. However the timing of the cosmic trigger will be slightly incorrect.

In order to study the importance of the Cerenkov effect, several measurements have been carried out on the guide at different distances from the PM and at several hitting angles (see table 4). In all these tests, the threshold voltage was -100 mV and the gain of the PMs was 10^8 .

Let us define the Cerenkov efficiency as the rate of particles traversing the light guide which produce detectable Cerenkov effect. In fig. 8 we present the defined Cerenkov efficiency versus hitting position, and in fig. 9 versus the incidence angle. We have estimated from the figures that we will accept less than 10% of Cerenkov triggers (with slightly shifted timing).

8.- TIME AND POSITION RESOLUTION.

The time resolution available with TOF measurements depends mainly upon three factors:

- a) *the features of the light pulse at the photocathode*: its time distribution shape up to the maximum and the number of photons; in other words, this involves the type of material or scintillator and the counter geometry. In figure 10 we show the arrival time distribution of the simulated pulse of photons at the photocathode, when a particle crosses the counter in the center with different wrappings.
- b) *the phototube characteristics*: The design of both the cathode-first dynode ($k - d_1$) region and the electron multiplier is critical in obtaining optimum time performance. In general, for the overall voltage, higher field strengths improve timing. The best timing is attained with high $k - d_1$ voltage and operating at maximum recommended gain. For the photocathode diameter, smaller diameters have better timing [11]. We show in figure 11 the transit time standard deviation of a *EMI9902KB* photomultiplier versus the number of photoelectrons arriving at the photocathode, for simulated and real pulses. We see that for less than 10 photoelectrons the temporal resolution becomes extraordinarily damaged.
- c) *the electronic treatment of the signal*, which introduces some dispersion errors ($\simeq 0.2ns$). The time resolution was studied by measuring the difference $\frac{t_2 - t_1}{2}$ that is directly related to the impact point in the scintillator. It is evident that there is an intrinsic uncertainty in the impact position determined by the trigger particle ($\simeq 6cm$) which corresponds to a time uncertainty of at least 0.15 ns given by the light speed in the plastic. This affects negligibly the time difference resolution $t_1 - t_2$, due to the fact that the timing-start provided by the trigger counters cancel. The larger errors come from the jitter in the PM's due to the low number of photoelectrons produced in average at the photocathode.

Both t_1 and t_2 have been walk time corrected: $t_{corr.} = t_{meas.} + \Delta t$ with

$$\Delta t = w \left(\frac{1}{\sqrt{a_0}} - \frac{1}{\sqrt{a}} \right) \quad (5)$$

where w is a parameter that we have experimentally determined, which mainly depends on the photomultiplier characteristics. a is the ADC value mesured for each TDC, and a_0 a reference ADC value.

Different techniques have been applied to obtain w : cosmic events located in the center of the detector and laser light of variable intensity injected on the detector. The obtained values agree very well for both methods: $w = 14.0 \pm 0.5 \text{ ns} \cdot pC^{1/2}$ where the error is only statistical. The fit can be seen in figure 12.

Figure 13 shows the quantity $\frac{t_2-t_1}{2}$, for 1000 particles crossing the detector in the center. The standard deviation of this distribution is

$$\sigma = \sqrt{\frac{\sigma_{t_1}^2 + \sigma_{t_2}^2}{2}} = 1.2 \text{ ns.}$$

This time resolution corresponds to a position resolution of 20 cms approximately.

The particle time of flight τ , given by the expression (7), is directly related with $\frac{t_1+t_2}{2}$. For the events without contamination of the Cerenkov effect, it does not depend on the crossing position. In Fig. 14 we represent the time of flight (or $\frac{t_1+t_2}{2}$) distribution and it can be observed that its standard deviation (compared to Fig. 13) is increased; this is due to the longitudinal size of the trigger counters and trigger PMs time jitter of our set up.

We conclude that the Time of Flight resolution is 1.2 nsec.

9.- CONCLUSIONS.

We have designed a large area TOF detector for DELPHI, which is stable and minimizes the occupied volume, using a semicylinder to bend 180 ° the light path.

A fast simulation program is described, which allows us to test all the experimental features of the detector.

The detection efficiency is almost 100%. The attenuation length is 135 cm and the effective speed of light in the scintillator 15.91 cm/ns.

The Cerenkov effect in the light guides will be observed in less than 10% of the events.

Finally and on the average, the spatial resolution is 20 cm and the time resolution 1.2 ns, which is in agreement with our previous design [1], and fulfils the requirements of the timing of cosmics and muons in Delphi.

10.- ACKNOWLEDGEMENTS.

We would like to express here our gratitude to Dr. A.Segura for his help.

REFERENCES

- [1] "DELPHI TECHNICAL PROPOSAL". DELPHI 83-66/1. CERN/ LEPC/ 83-3.
- [2] E. Sanchis, Ph. D Thesis. Valencia, 1987.
- [3] P. Allen et al. Nucl. Inst. and Methods **A277**, (1989), 347.
- [4] J. Cuevas, Ph. D Thesis. Santander, 1987.
- [5] J.A. Martinez, Ph. D Thesis. Valencia, 1988.
- [6] J.M. Benlloch et al. To be published in Anales de Fisica.

- [7] J.M. Benlloch et al. IFIC Internal note 89-1.
- [8] G. D'Agostini et al. Nucl. Inst. and Methods. **185** (1981) 49-65.
- [9] E. Sánchez, Tesina de Licenciatura. Valencia, 1986.
- [10] A. Ferrer et al. Anales de Fisica B83 (1987) 291.
- [11] THORN EMI. "*Photomultipliers* "

FIGURE CAPTIONS

Figure 1. Geometrical parameters of the TOF detectors and light guides. Note the 180° bending of the light guides, the length of the detector (3.55 m) and the thickness of the scintillator (1.9 cm).

Figure 2. Experimental set-up for Laser runs.

Figure 3. Coupling piece of the silicon fiber to scintillators.

Figure 4. Detection efficiency versus detection threshold.

- i) Black points stand for aluminated paper covering the bending semicylinder.
- ii) Crosses for aluminium deposited in vacuum.
- iii) Circles stand for 2 aluminium depositions.
 - a) $x = 0$. (in the center of the detector)
 - b) $x = + 1.5$ m

Figure 5. a) Efficiency of the prototype with the guides covered with aluminated paper. b) Equivalent number of detected photoelectrons versus threshold.

Figure 6. Attenuation length of the laser light in the scintillator.

Figure 7. Effective speed of the light in the scintillator.

Figure 8. Cerenkov efficiency versus distance of the particle hitting point to the PM.

Figure 9. Cerenkov efficiency versus incidence angle of the hitting particle.

Figure 10. Temporal probability distributions obtained by Montecarlo calculations for particles crossing the detector wrapped with aluminated paper in a) and wrapped with black paper in b). We can see the long tail of "slow" photons recovered by the aluminium.

Figure 11. EMI 9902KB time resolution versus number of photoelectrons for simulated pulses, and measured values.

Figure 12. W parameter for walk time correction.

Figure 13. $t_1 - t_2$ distribution for 1000 events.

Figure 14. $t_1 + t_2$ distribution for 1000 events.

TABLE 1

Characteristics of the NE110 plastic scintillator light signals.

Pulse Width	Decay Time	Rise Time	Att.Length	Wave Length Max. Emission
4.2 ns	3.2 ns	1.0 ns	400 cm	434 nm

TABLE 2Parameters of the N_2 Laser pulse.

Delay	Jitter	Wave Length	Pulsing Frequency
$300 \pm 100 ns$	2 ns	337.1 nm	0 – 100 Hz
Energy per Pulse	Pulse Width at half height	Beam Divergence	Beam Size
100 J/pul	$1 J \cdot ns$	4×2 m.v.d.	$6 \times 2 mm^2$.

TABLE 3

Characteristics of the Silicon Optical Fibers

Diameter of Fiber Core	Clading	First Cover	Numerical Aperture
$50 \pm 3 \mu m$	$125 \mu m$	$250 \mu m$	$0.21 \pm 0.02 \mu m$

TABLE 4

Tests performed on the Cerenkov Effect in the Liht Guides.

Test Number	Hitting Angle	Distance to PM (cm)
1	90^0	4
2	90^0	65
3	90^0	90
4	90^0	105
5	-45^0	55
6	45^0	55

TABLE 5

Missing and Remaining Photons in the TOF Detector.

A m.i.p. is supposed to hit in the center of the detector

	Losses (%)	Photons Left
Produced Photons		3.60×10^4
Solid Angle	46.8(%)	1.91×10^4
Each Direction	50(%)	0.96×10^4
Attenuation Length	76(%)	2.29×10^3
Reflexions in Bending	26(%)	1.70×10^3
Solid Angle in Bending	23.4(%)	1.30×10^3
Attenuation Length (Guide)	78(%)	286
Quantum Inefficiency	85(%)	43

Fig. 1

Fig. 2

Fig. 3

Fig. 4a

Fig. 4b

Fig.5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10 a

Fig. 10 b

Fig. 11

Fig. 12

Fig.13

Fig.14