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A 1152 Channel Time-of-flight System for an
Electromagnetic Calorimeter

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Abstract

A 1152 channel time-of-flight system used with a large electromagnetic calorimeter is described. The time of flight information was used to resolve ambiguities in the pattern recognition. A resolution of better than 0.25ns for all channels was achieved. The calibration methods employed to maintain this resolution over several years are discussed.

Introduction

The time-of-flight technique has been widely employed in high energy physics experiments. In the application described here, it was used to measure the position of showers in a 4m x 4m electromagnetic calorimeter studying direct photon production in hadronic collisions at CERN (Experiment WA70).

The calorimeter has been described in detail elsewhere (Ref 1,2). It consisted of twelve segments arranged in quadrants, each segment being made of ten layers of lead interleaved with sheets of teflon tubes with an internal diameter of 4.4mm filled with NE235 liquid scintillator (Fig 1). The sheets of tubes were alternately horizontal and vertical and the tubes were viewed by a total of 3072 Philips type XP2972 photomultipliers. In the first two segments of each quadrant the tubes were grouped to give a granularity of 1.07cm in the inner half of the detector and 2.14cm in the outer.

The time differences between signals from each of the 1152 photomultipliers in the first segment and a reference counter in the incident beam could be measured individually. When the delays through the cables and electronics were accounted for, the distance the scintillator light had travelled down the teflon tube could be uniquely determined, assuming that the particle producing the shower was travelling with the speed of light. This information was used to resolve the ambiguities in the pattern recognition (Fig 2).

The electronics, calibration methods and data analysis developed to achieve a resolution of typically $\pm 0.25\text{ns}$ for showers produced by photons of energy greater than 5GeV are described in the subsequent sections of this paper. Since the effective velocity of light in the scintillator was 19.4cm per ns, this time resolution corresponds to a position resolution of about $\pm 5\text{cms}$.

Electronics

The schematic arrangement of one time-of-flight (TOF) channel (Fig 3) shows the principle of the electronics. A constant current output from the overlap unit was started by a signal from the calorimeter channel and stopped by a beam counter signal. The time difference between the start and stop signals could be determined by digitising the total charge of this output.

The amplifier and discriminator were located close to the electromagnetic calorimeter and the overlap unit and the ADC were in the electronics counting room. The ADC gate was opened if the event satisfied the trigger conditions. The coaxial cable between the discriminator and the overlap unit provided a delay of 375ns for the decision making.

The TOF circuitry was driven by the positive signal from the next-to-last dynode, which had a dynamic range of 1.5mV to 300mV. The anode signal from each photomultiplier was used for pulse height measurements to determine the shower energy and a signal from the last dynode provided a fast trigger for the experiment. To reduce ground loop effects between the apparatus and the electronics counting room, 100 Ω resistors were inserted in the ground lines between the photomultiplier chain and the output cables of the two dynode signals.

A circuit diagram of the amplifier is given in Figure 4. The circuit used Plessey IC type SL565C and produced a voltage gain of 3.0 into 50 Ω with a power supply of 4.2V. Six amplifiers were assembled on each printed circuit card and mounted in a shielded box. The high bandwidth of the integrated circuit (>1GHz) produced amplification without deterioration in photomultiplier rise time (~ 1.5 ns 10% to 90%).

A circuit diagram of the discriminator is given in figure 5. The circuit

was based on the LeCroy IC type MVL100 which contained both a preamplifier and a comparator. The input threshold was controlled by an external voltage and was normally set to 4.5mV. In the quiescent state, the DC level of the output was -400mV to reduce time jitter in the overlap circuit. The output pulse had a width of 60ns and the output level during the pulse was -1000mV. Eighteen channels were packaged into a single width NIM module which also contained width and threshold controls and a test input facility. Time slewing in the circuit, driven by pulses between 2 and 20 times threshold from the detector, was 2ns. This was corrected offline by measuring the pulse heights from the photomultiplier anode outputs.

The overlap circuit logic is shown in Figure 6 and consisted of DC coupled start and stop signals switching a 12mA constant current source. The sensitivity of the constant current to temperature was 0.05% per °C. Twenty four overlap circuits were assembled, twelve per card, into a double width NIM module with an overall delay of 15ns per channel. An event in the calorimeter switched on the appropriate constant current supplies and these were switched off about 25ns later by a time reference signal from the beam. This time reference signal was shaped using a discriminator to 5ns FWHM and then strobed with the trigger logic, reshaped to 100ns, and fed to each overlap unit via logic fanouts.

The output from each overlap unit was fed through 1.5m of 50Ω cable into a LeCroy charge sensitive ADC type 2282C. This had a 12 bit ADC range with a sensitivity of 4 counts per pC. Each single width Camac unit contained 48 ADCs with a single 100ns gate pulse activated by the experimental trigger logic. Each Camac crate contained a processor that subtracted pedestals and also packed the output data by removing empty channels to minimise the overall Camac read-out time. One ADC count corresponded to a time change of about 20ps.

Determination of Shower Positions

For each channel triggering the TOF, the distance of the shower, d , along the direction of the scintillator measured from the inner edge of the quadrant was given by:

$$d = (c_0 N + c_1 + t_0 + t(A)) \times s \quad (1)$$

where N = TOF ADC counts for the channel.

c_0 = Calibration constant of the TOF ADC in nanoseconds per count

c_1 = Time interval to align the channel in time relative to the other channels

t_0 = Time interval to align all channels absolutely setting $d=0$ at the inner edge of the quadrant.

A = Anode pulse height in ADC counts

$t(A)$ = Time-slew due to the finite rise time of the input signal.

s = Speed of light in the scintillator.

The determination of the various factors in this equation using a laser and the experimental data is described below.

i) Calibration constant of the TOF ADCs, c_0

A laser fibre-optics system (Ref 3) was used to determine the calibration constant for each channel, in nanoseconds per ADC count. Once the photomultiplier voltages had been set to equalise the gains (Ref 3), this system was used to drive all 1152 phototubes together, to simulate a signal from the reference counter and to generate a trigger for the data acquisition system. By taking data with and without a known delay of 10ns in the common stop signal to the overlap units, the calibration constants for each channel could be determined. A typical value was 0.021 ns/count with a spread of $\pm 3\%$ over the 1152 channels. This calibration procedure was carried out every few

days during the experiment. The variations observed in the calibration constants were less than 1%.

ii) Relative time alignment, c_1

The laser data were used to measure the relative times of the 1152 channels and to produce a file of numbers to align all the channels in time in the offline programmes. This procedure aligned the channels to within $\pm 0.28\text{ns}$. Fine tuning the system with showers in the data as described later improved this by a factor of two.

iii) Time slewing effects, $t(A)$

Time-slewing effects in the discriminator due to the finite rise-time of the input signal became increasingly important as the input signal was reduced. Correction had to be made for these effects to improve the resolution of the position measurements, particularly for the lower energy showers.

The time-slewing was studied using a well-collimated electron beam striking the calorimeter at a known position. A parametrisation of the slew, adequate to make the correction, was found to be given by:

$$t(A) = \frac{c_2}{(A - c_3) + c_4} \quad (2)$$

c_3 = Anode pulse height in ADC counts at which the discriminator is 50% efficient.

c_2, c_4 = Constants determined by fitting the data.

In principle the constant c_2 could be different for each of the 1152 channels, since the ratio of the anode pulse height to the height of the pulse

triggering the discriminator could vary. In practice a single value of c_2 was found to be adequate.

The values of c_3 were determined for each channel from the data taken during the experiment and lay mostly between 9 and 15 counts. They were regularly checked and variations of more than one count were rare. A single value of c_4 was used for all channels.

The values of c_2 and c_4 used were found by fitting the data from showers recognised in the experimental data by the method described below in (iv). As would be expected the values obtained agreed well with the electron data, but this method had the advantage of averaging over all of the 1152 channels for photon showers. Figure 7 shows the observed slew with the fit superimposed.

iv) Absolute time alignment using the experimental data, t_0

In the direct photon experiment, the trigger selected events with a large deposition of energy in a limited region of the calorimeter. There were usually isolated showers in the event which could be unambiguously identified by matching the TOF information from the two views. Their positions were then known from the geometry of the tubes and this information could be used to establish the absolute time alignment.

Suitable shower candidates were selected by first searching for isolated groups of hits in both views in the anode pulse height information. The two views were then matched by requiring that the difference between the TOF measurements for the two views agreed with the known geometry of the scintillator tubes involved to within $\pm 20\text{cm}$ ($\pm 1\text{ns}$). This matching procedure was independent of the alignment relative to the beam reference counter. A comparison of the TOF measurement of one coordinate with the known coordinate from the other view could be used to establish the alignment relative to the

reference counter.

v) Fine-tuning of the system

Once the alignment relative to the reference counter had been determined, it was found that the relative time alignment obtained from the laser data could be improved by a factor of two using the information from the isolated showers. Furthermore, by comparing the TOF measurements along the two metre length of the tubes of scintillator with the known position of the shower, the speed of light in the scintillator and the length of the delay cable used in the calibration was checked to 0.5%. To obtain adequate statistics in channels far from the beam, a full data tape of 30000 events had to be analysed. This was done after every laser calibration and a file of constants c_0 , c_1 and c_3 for each channel was produced to convert ADC counts from the TOF system to position in the calorimeter.

The Time Resolution of the System

It is convenient to discuss the resolution in terms of independent contributions from the time-jitter in the start pulse, the jitter in stop pulse, the spread in time alignment of the 1152 channels and any electronic drift.

1) The time-jitter in the start pulse, σ_1

This contribution was due to the statistical variations in the triggering of the discriminator and was studied using the electron beam data. The time alignment and drift contributions were essentially negligible in this data because only a few channels were considered with good statistics accumulated in a short time. The contribution from the common stop pulse could be removed

by taking the difference between the orthogonal channels. The width of the spectrum of this difference arose from the jitter on the two independent start pulses. An example of this spectrum when both pulse heights were large is shown in figure 8.

The variation of the standard deviation of this time difference with the height of the start pulses could be accounted for by parametrising the jitter from a single channel by the form

$$\sigma_1 = 0.077 + \frac{10.2}{(A - c_3) + 9} \quad (3)$$

where A and c_3 are defined as before and the units of σ_1 are nanoseconds.

ii) The time-jitter in the stop pulse, σ_2

Taking the spread in the TOF measurement for one coordinate of the electron data to be the sum in quadrature of the jitter in the start and stop pulses, the jitter in the stop pulse was estimated to be $\sigma_2 \sim 0.24\text{ns}$. In the experimental data, this was improved on an event by event basis using unambiguously matched showers whose positions were known from the geometry of the calorimeter to find an average stop time. The principle of matching the views to identify the showers was the same as that described earlier: the difference between the orthogonal coordinates measured by the TOF system had to agree with the geometry of the scintillator tubes. In this procedure, the difference, converted to time by dividing by the speed of light in the scintillator, had to be within $\pm 1.5 \sqrt{(\sigma_{1y}^2 + \sigma_{1z}^2)}$ where σ_{1y} and σ_{1z} were calculated from (3) for the y and z views. In addition, simple cuts in the relative anode pulse heights in the two views were used to clean up the data. For each match, the shift of the stop pulse required to optimise the alignment of the TOF channels gave a measure of the time of the beam reference

particle relative to some standard time. On the average the stop pulse jitter was reduced to 0.18ns.

iii) Spread in the time alignment and electronic drift, σ_3

These contributions were estimated from the experimental data using the unambiguously matched showers. The distribution of the difference between the TOF position measurements and the known shower coordinate could be fitted adequately by a Gaussian. The standard deviation of this distribution, σ , converted to time by dividing by the speed of light in the scintillator, was taken as the resolution of one channel of the TOF system. Figure 9 shows σ as a function of the anode pulse height when the reduction of the stop pulse jitter is included. Taking:

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2} \quad (4)$$

with σ_1 given by (3), the spread in time alignment and any electronic drift, σ_3 , was found to contribute about 0.14ns

The Performance of the System

The system has been in operation for three years with very few faults. During a typical data acquisition period of six weeks the largest source of time drift (<200ps in 24 hours) was in the beam reference counter which was operating at a frequency of 10MHz. However this affected all channels equally and was easily removed using the procedure of finding the stop time from the data.

In the analysis of the experimental data, the TOF information was used in several ways:

- i) It resolved ambiguities in the pattern recognition in the detector. Figure 10 shows the resolution of the shower coordinate from the TOF information as a function of the shower energy observed in the data. When more than one channel contributes TOF information about the coordinate, a weighted mean was taken. The shower energy was calculated from the pulse height information in the three segments of the calorimeter. A resolution of about 5cm was achieved for showers greater than 5GeV.
- ii) The procedure of determining the stop time also enabled double events, which produced two clusters of stop times, to be recognised when separated by more than 2ns
- iii) Random coincidences between the beam particles and the event in the calorimeter could be rejected if the average stop time was found to be more than 1.2ns from the standard time.

Conclusion

The system described achieved a time resolution of better than 0.25ns for each of the 1152 channels. The use of a laser together with the experimental data for calibration, fine tuning and monitoring has enabled this resolution to be maintained over several years.

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Figure Captions

- Figure 1 (a) The geometry of the calorimeter, showing the four quadrants (Q) and the three segments(S).
- (b) The structure of the outer corner of one segment showing the lead (Pb) and the tubes of scintillator (Sc). Light from groups of tubes in the five layers in a given direction was mixed and fed to one photomultiplier. Groups of two tubes gave a granularity of 1.07cms.
- Figure 2 The figure illustrates the ambiguity in pattern recognition in a single quadrant resolved by the time-of-flight information represented by the horizontal and vertical bars ($\pm 1\sigma$). Matching the pulse height information in the views, shown for the first segment only in the figure, does not distinguish clearly between positions A and B and positions C and D.
- Figure 3 (a) A single time-of-flight channel.
- (b) Timing of pulses at the overlap unit.
- Figure 4 Circuit diagram of the amplifier
- Figure 5 Circuit diagram of the discriminator. The voltage controlling the threshold and the width of the output pulse are common to the eighteen discriminators in each single width NIM module. The same test input drives all eighteen discriminators. The OR output of the eighteen discriminators is also available.

Figure 6 Circuit diagram of the overlap unit. A common stop signal from point A is used for the twenty four overlap circuits in each double width NIM module.

Figure 7 The time-slew of the discriminator as a function of the anode pulse height. The threshold of 13 ADC counts corresponds to an input pulse to the discriminator of 4.5mV. The curve is the fit of equation (2) of the text with $c_2 = 100$, $c_3 = 13$ and $c_4 = 24$.

Figure 8 The time difference between two orthogonal channels with anode pulse heights greater than 700 ADC counts produced by a 50GeV electron. The dashed curve is a Gaussian fit with $\sigma = 0.13\text{ns}$

Figure 9 The time resolution of the system as a function of the anode pulse height. The full curve is a fit to equation (4) of the text with σ_1 given by (3). The dashed curve shows the contribution from σ_1 alone.

Figure 10 The position resolution for one coordinate as a function of shower energy for isolated electromagnetic showers.

(a)

(b)

FIG 1

FIG 2

(a)

(b)

FIG 3

FIG 4

FIG 5

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FIG 7

FIG 8

FIG 9

FIG 10