PARTICLE DISCRIMINATION USING SUB-OPTIMAL FILTERING TECHNIQUES

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Abstract

The discrimination of high energy electrons and pions using a scintillating fiber calorimeter is addressed. The discrimination method is based on analysing the time structure of calorimeter signals and achieves discrimination response smaller than 100 ns. Signals pass through a high performance constant fraction discriminator and events that lie in the confusion region of this discriminator are analysed through a sub-optimal filtering technique based on pulse integration. The composed discrimination system achieves 98% electron efficiency with less than 0.1% of pions being misclassified as electrons.
Key words: Instrumentation, Optimal Filtering, Particle Discrimination, Detectors.

INTRODUCTION

In modern high energy physics experiments, calorimeters are being considered of increasing importance due to some interesting features they exhibit. These detectors are basically used for energy measurement, as they totally absorb the energy of the incoming particles. Due to differences in the way particles deposit their energy inside these detectors, modern experiments also use calorimeters for particle identification .

Scintillating fiber calorimeters are amongst the fastest detectors and they are present in a variety of experiments that are currently running. A succesful version of this type of calorimeter [1] is based on a large number of scintillating plastic optical fibers (with a diameter of 1 mm and a length of 2.20 m) embedded in a lead matrix. The overall structure of the detector can be seen in Figure 1.

Figure 2 shows a typical signal resulting from the interection of a 150 GeV electron with such a calorimeter. This signal was recorded with a fast (1 GSample/sec) digital storage oscilloscope and results from adding the signals of the seven innermost modules (with respect to the impact point of particles in the detector). The full-width half maximum of such signals is of the order of 5 ns.

In Figure 3 we can see two different classes of pion events interacting with the same detector. In (a), a typical pion with a double peak signal structure can be seen. This is due to the fact that the front face of the calorimeter is made reflective by deposing aluminium in the exit surface of the fibers. As pions, in average, start showering deeper in the calorimeter, part of the light is reflected by the mirror in the front face of the detector and adds up to the rest of the light that travelled directly towards the light detector (in our case, a photomultiplier tube) placed at the other end of the fibers. For pions that start interacting almost immediately in the detector (like electrons do), this double peak structure is not observed (see Figure 3 (b)).

As fiber calorimeters develop very fast signals, the above differences in the calorimeter signal structure can be used to accomplish a fast and accurate electron/pion discrimination system. The method is very attractive for experiments characterized by very high event rates, so that real time validation systems, that can identify whether an event is representative of the physics one wants to observe in the experiment, can be built based on the signal response of this detector [2].

Here, we address electron/pion separation with analog signal processing techniques, building a sub-optimum filter discrimination system. We have chosen this approach inspired in the well known ability of optimum filters in treating random signals with high accuracy and speed, which are the most important requirements to be met in this problem. Unfortunately, optimum filters present difficulties in terms of realizability, so that typical designs finish approximating the impulse response of the original optimum filter. Thus, we

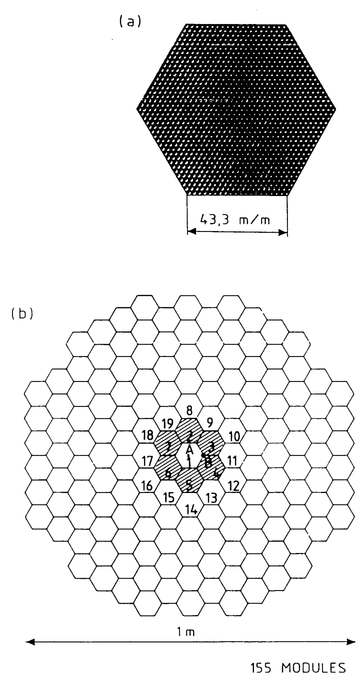

Figure 1. The structure of one calorimeter module (a) and the layout of the detector (b).

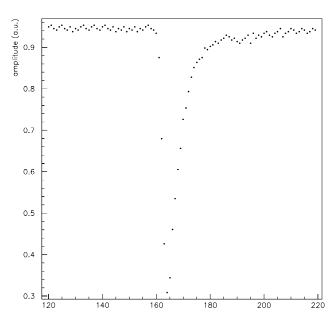

Figure 2. Typical electron signal.

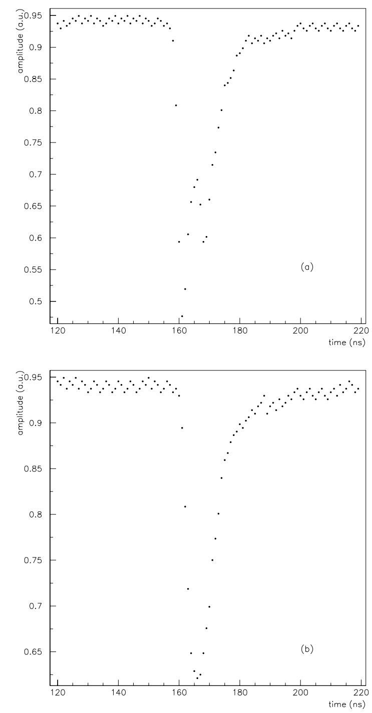

Figure 3. Classes of negative pion signals, including double peak structure (a), and pulse shape similar to electron pattern (b).

can search for a fast sub-optimal technique that could be easier to implement and still keep performance near its theoretical optimum level.

In what follows we discuss the topics involved in system design. A filter for unfolding the instrumental effects on calorimeter signals is described in details. Then we develop a composite discriminator using the sub-optimum filter. This last filter acts in conjunction with a constant fraction discriminatior, so that electrons can be separated from pions with very low discrimination error.

All data included in this work have been taken from tests with electron and pion beams from the Super Proton Synchrotron at CERN (Switzerland). The data covers an energy range of 40-150 GeV, using two different impact points: the center of the central module and the common corner of three modules. We have used a calorimeter prototype with 19 modules, which was constructed in preparation for the construction of a larger detector with 155 modules. The fibers used were of the type SCSN-38 from Kurary Co. Ltd.

The already mentioned sum of seven signal was selected to be the discriminating signal. This selection comes from the fact that electromagnetic showers are well contained in a cluster of three neighbouring modules and about 80% of the pion signal is contained on these seven modules.

A specially designed mixer for very fast pulses [4] was used to build the sum of seven signal with minimum distortion.

SYSTEM CHARACTERIZATION

The electron/pion separation method developed here is based on exploiting subtle differences in the time structure of the calorimeter signals. In order to achieve high efficiency in this discrimination, one can think of developing a method that would enhance the differences between these signals. This can be achieved by removing contributions to the calorimeter signal that originate from sources different of the physics of the shower development. The compensation for instrumental effects on calorimeter signals may help descovering the actual structure of the signals developed by electrons and pions, and better discrimination performance can be expected when these cleaned pulses are fed into the discriminating system.

The calorimeter can be modeled as a linear system for which subsystems involved in data acquisition distort the original response for pions and electrons. This means to characterize components in the acquired signals which would be common to both signal patterns and could be physically identified with a subsystem.

Two subsystems can be cosidered as playing the major role in the overall system transfer function: the photomultiplier tube (PM) and the signal transmission cable that carries the calorimeter output signal to the data acquisition system which is involved in signal digitalization.

In order to characterize each subsystem, different experimental procedures were used. For identifying the cable subsystem (type C-50-6-1), we digitized the cable response to a fast step input signal. Then, using a three exponential fitting to cable's impulse response [5], we could successfully compensate the cable's transfer function $G(s)$, which was found to be given by

$$G(s) = \frac{(s + 0.131)}{(s + 0.111)(s + 0.868)(s + 4.43)} \quad (1)$$

Here frequencies were normalized to 1 Grad/s. In practice, the pole at 4.43 Grad/s can be considered extremely high and, in fact, had minor effects on the overall signal response. Therefore, for circuit implementation only the other two poles were considered.

The photomultiplier subsystem was modeled as having a Gaussian impulse response. For extracting parameters, we took single photoelectron data from the PM used (Philips XP 2282). The approximated Gaussian function is, however, quite difficult to be accomplished in practice [6], which has led us to consider zero-mean Gaussian function characterization for the PM's impulse response. This particular Gaussian signal can in practice be realized with a multiple pole transfer function [7] and, in our case, a double pole in the frequency of 1.98 Grad/s was used.

In order to compensate for the instrumental effects introduced by thsese subsystems, and extract more accurately electron and pion signatures, the filter transfer function, $H(s)$, should be the inverse of system function:

$$H(s) = \frac{(s + 0.111)(s + 0.868)(s + 1.98)^2}{(s + 0.131)} \quad (2)$$

The compensating filter was implemented using pole-zero sections [5]. As the transfer function in (2) has more zeros than poles, the missing poles required for circuit design would come from parasitic poles (appearing in higher frequencies, far from the frequency range of interest) introduced by the wideband transistors used to implement filter sections.

Figure 4 shows how the filter circuit compensates for such effects on calorimeter signals. It can be seen that the pulse at filter output is free of a tail present in the original calorimeter signal. It is also noticeable from this figure that original pulses are shortened by the compensation filter, a feature that helps achieving faster discrimination time.

DISCRIMINATION SYSTEM

As pion signals usually have double peak structure, which widens these signals, and electrons are free of such effect and, consequently, are faster, a discrimination method based on measuring the signal width should be quite efficient. In fact, it was shown that a constant fraction (CF) circuit with a discriminating level of 20%, named Full Width at one Fifth Maximum (FWFM), is a good method for detecting the humps present on pion signals [2]. However, pions without humps can easily be misclassified as electrons by the constant fraction discriminator. For such pulses, some extra signal processing will be required for improving particle identification. For 80 GeV particles, the CF discriminator achieved 99.7% electron efficiency with 0.12% of pions misclassified as electrons.

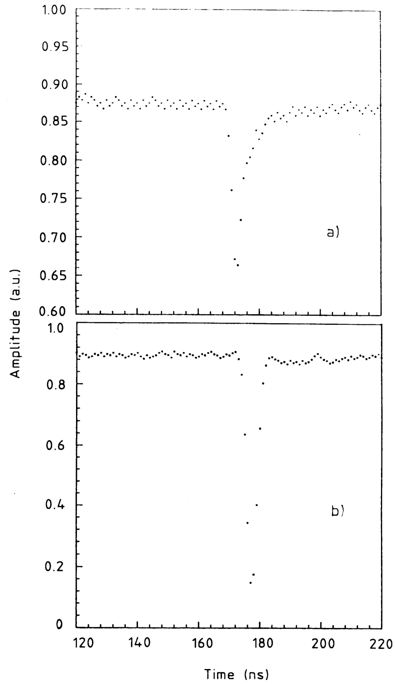

Figure 4. Filtering action on electron signals: original digitized pulse (a), and after removing the instrumental effects (b).

Hence, one can think to use a constant fraction unit to identify the majority of pions due to the presence of humps in the signal. These signals are wide enough to be surely recognized as pions. When the incoming signal does not pass the conditions of the constant fraction unit, and thus becomes an electron candidate, it can be fed into the input node of the compensation filter and the resulting signal can be analysed by another discrimination procedure.

One possibility is to use another constant fraction unit to discriminate filtered pulses, which proved to improve up to 50 % the performance of a single constant fraction discriminator for a similar but projective calorimeter [3]. Another approach uses a constant fraction working in parallel with more sophisticated filters, as we describe next.

It's well known that optimum filtering [8] optimizes the signal to noise ratio when we have a random signal at its input with additive white noise pertubation. Unfortunately, the optimum filter technique generaly imposes an approximation step, due to the complexity of the waveform to be matched or realizability conditions [8].

Here, we develop an alternative technique that could treat the problem in a simpler way but

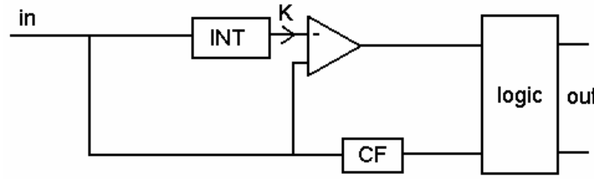

Figure 5. Block diagram of the sub-optimum filter discriminator.

still with good performance. Firstly, it should be noted that constant fraction discrimination uses only three main samples in the analysis of the incoming pulse: the peak and the values in the rise and fall times that cross the 20% level of discrimination. On the other hand, optimum filters make use of the overall pulse structure, as the impulse response of such filters is the mirror image of the signal pattern to be identified.

The proposed method tries to improve the constant fraction method by having optimal accuracy in the discrimination level for each event. To do this, the incoming pulse is integrated and the discrimination level is determined by a fraction of this value, so that discrimination stays around the optimum 20% level. This means that the discrimination level fluctuates around the 20% level according to the specific characteristics of each signal. We refer to this discriminator as a sub-optimum filter, as it uses the full pulse structure only to determine the discrimination level of a constant fraction width measurement. Therefore, it can be considered as an approximation of the optimal filtering performance.

This discrimination scheme can be seen in Figure 5. In this scheme, the logic unit considers the output of the sub-optimal branch when the incoming pulse has a width measured by the CF unit smaller than a given threshold, which indicates the presence of an electron candidate. The final classification is achieved by stablishing another cut on particle distributions of the sub-optimal branch.

The determination of parameter K is, in principle, dependable of the energy of the incoming particle. In order to make the proposed method invariant with respect to the energy level, we can use the peak of the incoming pulse to normalise the discrimination level. The use of peak value as a translator of pulse energy is possible due to the fact that pulses without double peak structure basically scale up their peak value with increasing energy, while the main characteristics of pulse shape are practicaly kept unchanged. This is not true for pulses with humps, as the hump level highly fluctuates from signal to signal. However, the class of pulses with double peak structure do not arrive to the suboptimum filter, as pulses belonging to it are immediately identified as representing pion events by the constant fraction unit.

Thus, parameter K can be set equal to

$$K = \frac{0,2P_0}{I_0} \tag{3}$$

with $P_0 = E[max f(t)]$ and $I_0 = E[\int f(t)dt]$ representing, respectively, the mean peak and the mean of the integral for electrons and for a given energy (80 GeV in our case). Electrons are chosen to set both mean values as they deposit almost all their energy inside the sevem modules used to build the discriminating signal. Using (3), the discriminating level of the suboptimal filtering system for a given pulse $f(t)$ will be given by

$$d = \frac{0,2P_0 \int f(t)dt}{I_0} \tag{4}$$

Equation (4) shows that the energy information is obtained from the peak value of the pulse, as we described above. For instance, if the incoming pulse is of 40 GeV, its peak value will be $\sim P_0/2$ and the integration of such pulse will produce a value $\sim I_0/2$. Thus, the discrimination level will be kept around the desired level of 20%.

The proposed discriminating system was tested on experimental calorimeter data. After simulating a FWFM constant fraction discriminator with 100 ps resolution, a threshold value of 12 ns was set as the width above which events were identified as pions by this unit.

The composed discriminator was simulated and its performance was $\sim$ 30% better than the one obtained using a single constant fraction discriminator. When calorimeter signals were fed into a digital version of the compensation filter, the discrimination performance did not improve significantly. Figure 6 shows the distribution of the measured pulse widths obtained from the composed discriminator.

The sub-optimum filter can be realized in the way shown in Figure 7. Video amplifiers can perform the buffer blocks shown in the figure, in order to isolate the input signal and the signal sent to the comparator. A matched delay line (a 50 Ω cable) is used to delay the incoming signal till the integration procedure had been performed. The integration is realized with a time constant $\tau =$ RC matching the fast time constant of an exponential function modeling the decaying characteristic of a typical electron pulse. By doing this, the gate width for performing integration of the incoming signal is kept minimum, as a mismatched delay line is used to switch off integration after a time controled by the cable length and its line resistor. In this way, the integrated signal returns faster to the baseline and pileup effects are minimised. At the output of the comparator, the width of the incoming pulse can be measured, according to the level set by the integrator.

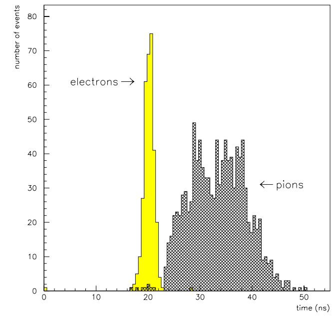

Figure 6. Signal distributions of the sub-optimum discriminator.

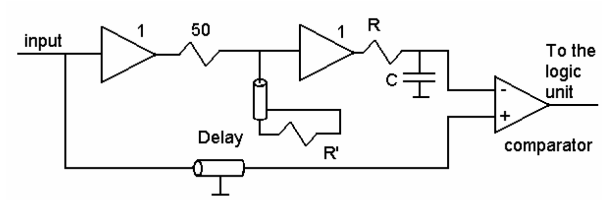

Figure 7. Realization of the sub-optimal filter discriminator.

As signals are shortened by the compensating filter, cascading this filter with the suboptimum filter may produce faster processing times, depending how fast the CF unit operates. As FWFM of signals are smaller than 30 ns, an overall processing time of 60 ns is feasible.

CONCLUSIONS

A fast electron/pion discriminator for a fiber calorimeter was developed. It was shown that an improvement in the electron identification is achieved when a constant fraction method (FWFM) is used in conjunction with a sub-optimum filter discriminator. This filter integrates signals that pass the conditions of the constant fraction unit and sets a discrimination level for measuring the signal width around 20% of the signal peak value. By extracting information of the full signal to set the discrimination level, the filter tries to identify better the optimum discrimination level adapted to a given pulse.

The proposed discriminator was able to improve in about 30% the performance of a single constant fraction discriminator, achieving 98% electron efficiency with less than 0.1% of pions misidentified as electrons. If the discriminator is used in conjunction with a filter that removes instrumental effects in the signals, the performance was not improved. Possibly, as the compensation filter increases frequency bandwidth, the noise level of the discriminating points set by the sub-optimum filter may increase and disturb the analysis of the composed discriminator.

To overcome this effect, one alternative is to discriminate integrated calorimeter signals, which would decrease the noise level and allow the discriminator to profit from the cleaner patterns provided by the compensating filter. In fact, preliminary results of this approach point out that the discrimination error for pions can be further reduced by 15%, when it is measured the time required for integrated pulses from filter output to go from 20% to 80% of their final values.

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