High p_T trigger electronics for a large orthogonal readout electromagnetic calorimeter

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Abstract: A trigger system has been designed and built to select events containing high p_T electromagnetic showers detected in a large calorimeter with orthogonal readout. The electronics include analogue adders with up to 123 inputs, pulse shapers with 20 ns integration time, 100 MHz flash ADCs and ECL look-up tables. The total number of input channels is 3072 and the trigger decision is made in about 120 ns.

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1. Introduction

A large electromagnetic lead-liquid scintillator calorimeter [1] has been built to study high transverse momentum (p_T) direct photon events produced in hadronic collisions in experiment WA70 at the CERN Omega spectrometer. An event trigger consists of a target interaction, defined by beam counters, in coincidence with a "calorimeter trigger". The calorimeter trigger is designed to select high p_T photon candidates above a given threshold, typically 3 GeV/c with a beam intensity up to 5×10^7 particles per 1 s burst. An important feature of the calorimeter is the orthogonal readout, which makes a high p_T trigger system difficult to implement. In contrast similar trigger systems operating on tower structure calorimeters are rather common.

The calorimeter trigger system, which is a custom-made device built at the University of Geneva, is described.

2. The calorimeter

The calorimeter (Fig.1) is located 10.9 m from the downstream end of a 1 m long hydrogen target. It consists of twelve (2.054 m x 2.054 m x 10.4 cm) segments arranged in quadrants, each three segments deep. A segment consists of ten sheets of lead (4.2 mm thick), interleaved with ten layers of teflon tubes (4.4 mm in diameter) filled with NE235 liquid scintillator, giving a total of 24 radiation lengths for each quadrant. The scintillator tubes, arranged to give orthogonal readout, are grouped in the first two segments to form channels 1.07 cm in width in the first metre close to the beam and 2.14 cm in width for the outer region before being coupled to photomultipliers. The third segment of each quadrant consists entirely of 2.14 cm wide channels. The light attenuation inside a scintillator tube can be represented by a sum of two exponentials¹ and varies by about 2% from tube to tube. The complete calorimeter has 3072 photomultipliers (Philips XP2972 [2]), each having an individually stabilized and computer-controlled high voltage supply (LeCroy type 1440). The anode outputs are connected

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$I = I_0(0.24 \exp(-x/50.6) + 0.76 \exp(-x/278))$ for distances "x" between source and detection extending from 40 cm to 240 cm.

to LeCroy charge sensitive ADCs (type 2282C) through 80 m of coaxial cable. This provides a 400 ns delay for the electronic decision logic before the ADC gates are opened.

3. The calorimeter trigger

Important factors in the design specification of the trigger system are:

a) The interaction rate is high (up to 5×10^6 per 1 s burst).

b) The calorimeter has Y/Z orthogonal readout, whereas the trigger must select events according to their transverse energy E_T given by

$$\sqrt{(E_{Ty}^2 + E_{Tz}^2)}$$

c) The large multiplicity of electromagnetic showers in a high p_T event leads to ambiguities in Y/Z associations.

d) The light attenuation inside the teflon tubes results in an attenuation factor of 2.4 over the length of a scintillator tube.

These requirements have resulted in the following scheme:

Each quadrant is divided into four horizontal bands and four vertical bands, thus defining 16 trigger cells. The last dynode signal of every photomultiplier is individually attenuated by a resistor proportional to $1/\sin\theta_y$ or $1/\sin\theta_z$, where θ_y and θ_z are the angles subtended by the photomultiplier channel with the beam line (Fig.1). This technique gives signals proportional to E_{Ty} or E_{Tz} . All of the signals in a band are then summed and digitized by a flash ADC. The outputs of the flash ADCs address a bank of ECL memories (a look-up table) pre-programmed to decide whether the energy deposited in a given trigger cell corresponds to a transverse energy above a defined threshold. The look-up table takes into account the light attenuation in the scintillator as well as the energy balance between the two views. The partition of the calorimeter into trigger cells and the programming of the memories with different light attenuation corrections, depending on the position of the trigger cell relative to the photomultipliers, solve the problems raised by points c) and d). The memories have several output bits to provide different trigger conditions running in parallel (e.g. different p_T thresholds). In

this respect, the use of a look-up table allows great flexibility in trigger definition. By using down-scaler units, the different trigger types can be mixed in suitable proportions to keep the dead time sufficiently low. It is possible to demand coincidences between different quadrants.

The operation of such a trigger system can be understood as follows: the electronics associate the transverse energy (E_{TZ}) collected in a given horizontal band with the transverse energy (E_{TY}) found in each of the vertical bands. These 16 combinations per quadrant are tested in parallel with their corresponding light attenuation corrections. If one of these combinations gives a transverse energy above threshold and if an approximate requirement of energy matching ($E_Y \cong E_Z$) is fulfilled, the corresponding trigger cell is flagged. This provides a fast hardwired pattern recognition system capable of detecting high transverse energy clusters.

4. Functional description and implementation

Ideally a large number of small trigger cells should be used to give a high probability of selecting a single shower rather than an energy cluster deposited by more than one particle. It would also result in a more accurate determination of the transverse energy as the corrections applied for light attenuation are the same wherever the shower originates inside the cell. The division of each quadrant into four bands horizontally and vertically is therefore a compromise between the accuracy in the E_T measurement of a single shower and the complexity of the subsequent electronics.

A Monte-Carlo simulation has been used to optimise the different parameters of the trigger system. It shows in particular the advantage of combining the signals from the three segments of the calorimeter. For channels with a Y or Z coordinate close to that of the beam line, the projected transverse energy signal (E_{TY}, E_{TZ}) generated by attenuating the photomultiplier signal becomes small (i.e. the signal is reduced to zero for channels at the same Y or Z as the beam line). In such situations, it becomes impossible to regenerate the E_Y/E_Z signals to perform the energy balance between the two views of the calorimeter. The Monte-Carlo study indicates that limiting the largest attenuation factors to 20 allows an approximate energy balance cut to be made to increase the trigger selectivity, while

creating an acceptably small bias. It also permits a threshold of one flash ADC count to be set in the E_{Ty} and E_{Tz} signals. This reduces the sensitivity to random triggers from photomultiplier noise by demanding a coincidence between the two views. The study also concludes that a 4-bit flash ADC (16 levels) provides a p_T cut-off sufficiently sharp for the experiment when each quadrant is divided into 16 cells. This leads to the following arrangement for each of the four quadrants (Fig. 2): a) Eight adder modules, b) One shaper module, c) Two flash ADC modules and d) A memory module.

a) The eight adder modules are located close to the calorimeter. They are connected to the last dynode of the photomultipliers by 4 m cables and sum all the signals inside each of the eight bands. Starting from the beam, the width of the four horizontal (vertical) bands are 25.7 cm, 52.4 cm, 65.3 cm and 66.3 cm. These band widths correspond to 60, 123, 117 and 93 photomultipliers respectively, over the three segments, with a band overlap of three photomultipliers, one per segment. The overlaps are included to avoid missing a shower split between two bands. The Monte-Carlo simulation has shown that this overlap width is sufficient for a good trigger efficiency. The weighting resistors for transverse energy correction are located in the adders.

b) The shaper module along with the rest of the trigger electronics is located in the counting room. It consists of eight pulse shaping amplifiers and logic for a first level trigger. The shaping amplifiers are coupled to the adders by 19 m of fast cable². These amplifiers have a 20 ns integration time suitable for the flash ADCs to which they are connected. This short integration time is justified by the fast response of the calorimeter [1]. The outputs of the amplifiers are bipolar signals with a pulse height proportional to E_{Ty} or E_{Tz} from the corresponding band. As the transit time in the calorimeter changes with the position of the shower relative to the photomultipliers, individual strobes timed on the maximum of the different E_{Ty} , E_{Tz} signals are sent by peak-finding logic (section 5.2) to the corresponding flash ADC. The first level trigger demands that at least one of the eight E_{Ty} or E_{Tz} signals be above a given threshold in order to retain only events with a signal in the calorimeter. If this condition is fulfilled, strobes are sent to reset flash ADCs corresponding to empty bands (i.e. with no signal above the peak-finding logic threshold) and to trigger the look-up table.

² Norsk Elektrisk 6300; $v/c=0.83$; 75 Ω .

c) The two flash ADC modules are each equipped with four 100 MHz 4-bit encoders, which digitize the E_{Ty} and E_{Tz} signals from the eight bands. The output lines provide DC levels. This allows the information to be held until the arrival of the next strobe (or reset strobe) pulse.

d) The memory module (look-up table) is essentially a set of 16 ECL memory chips, 256x4 bits. The 8-bit address lines of each chip are connected to the flash ADC modules according to the special pattern illustrated in Fig. 2 (4 lines are linked to a vertical band and the other 4 lines to a horizontal band). A memory pattern, which selects $E_T = \sqrt{(E_{Ty}^2 + E_{Tz}^2)}$ above a given threshold, can then be loaded. In addition, this hardware configuration defines a simple correspondance between the 16 chips of the memory module and the 16 trigger cells of a calorimeter quadrant. It is then simple to alter the initial memory pattern to take into account the average light attenuation correction depending on the position of the trigger cell relative to the photomultipliers. Memories are loaded to request at least one flash ADC count in both views. It is also possible to demand an energy balance between the horizontal and vertical bands, although a bias may be introduced by additional showers located in the corresponding bands but outside the trigger cell. As memory chips have four output bits, they can be loaded with four different conditions defining four trigger types running simultaneously.

The memory module provides 100 output signals, 25 for each type of trigger as follows:

- i) The "OR" output of the 16 memory chips (quadrant trigger signal).
- ii) 8 partial "OR" outputs, one for each row and column of the memory chip matrix.
- iii) 16 outputs, one from each memory chip.

Except for the quadrant trigger signal output, most of these outputs are intended for future extensions of the trigger system such as: an electron trigger using a coincidence with wire chamber information, a multiplicity trigger, a total E_T trigger, etc.

It should be stressed that the full trigger scheme relies on the assumption of a good photomultiplier gain equalization (better than $\pm 5\%$). The equalization procedure is described in detail in [6]. The calibration of the trigger system itself is achieved by a pulse generator module which injects signals into the adders to simulate those from the photomultiplier dynodes, using charge defined by a 12-bit DAC. Moreover all flash ADC modules have a built-in 8-bit DAC device for additional tests of the encoders and of the look-up table.

5. Electronic circuit details

5.1 *The adder module*

The adder circuit uses Plessey SL560C amplifiers set in cascade (Fig. 3). Up to 23 inputs are connected together, each through a different weighting resistor, and fed into a single amplifier. Six of these amplifiers are used at the front end of the circuit giving the sum of up to 123 photomultiplier dynode signals. Every front end amplifier is also connected to the test pulse generator in order to detect any faulty chips. The adder printed board is packed in a single width NIM module without a standard NIM back connector, the +12 V being supplied via a 2-pin connector. To make more room for the large number of cables feeding each adder, the 4 m coaxial cables from the last dynodes of the photomultipliers are passed through an opening in the front panel and are soldered directly to the printed circuit board of the adder. As each band has an overlap of three photomultipliers with the next band, there are three outputs for duplicated photomultiplier dynode signals to be sent to the next adder (starting from the calorimeter centre) and three inputs to be fed from the previous adder. These can be connected by very short cables (0.5 ns).

The weighting resistors have an accuracy of 1%. The bandwidth of the adder circuit is 130 MHz with a linearity better than 2% and the total transit time inside the circuit is 6 ns.

5.2 *The shaper module*

The shaper module is a triple width CAMAC unit. Two of the printed circuit boards are identical and each has four similar sections consisting of a pulse shaper, three discriminators and reset logic. A third board, located in the middle, connects with the CAMAC bus. It contains the DACs for the discriminator thresholds, the readout memories for the discriminator status word and the logic for the first level trigger. A schematic layout of the circuit is given in Fig. 4. The three discriminators per channel are called "zero crossing", "low" and "high discriminator" because of their relative threshold value.

Each pulse shaping amplifier consists of an integration stage followed by two delay line clipping stages, each with a 20 ns clipping time. It is made of transistor arrays with a gain adjusting potentiom-

eter accessible from the front panel. In response to a positive input pulse, it provides a bipolar signal with 40 ns lobes. The amplitude of the first lobe, which is positive, is proportional to the charge of the input pulse. The output is connected to the flash ADC. The bipolar signal provided by the shaper is also fed into three discriminators (LeCroy MVL100) in order to generate two types of strobe, one for the flash ADC, the other for the memory module. The flash ADC strobe is timed on the maximum of the positive lobe of the bipolar pulse. It is supplied by peak-finding logic which consists of a discriminator detecting the zero crossing of the bipolar pulse and the "low discriminator" which inhibits the strobe if the signal is below a given threshold, typically below one flash ADC count. The memory strobe is given by the logical "OR" of all the "high discriminators". This means the memory module is only interrogated when there is a signal in the calorimeter quadrant and this defines a first level trigger. If this condition is fulfilled, the pattern of the "high" and "low discriminators" which have fired is memorised and can be read by CAMAC (discriminator status word). The loading of the thresholds is done by CAMAC with two 8-bit DACs, one for the "low discriminators", the second for the "high discriminators". As the digital outputs from the flash ADCs are held until the next strobe pulse arrives, reset logic sends a strobe to every flash ADC whose input signal is below the peak-finding logic threshold if the first level trigger is fulfilled. These flash ADC outputs which correspond to a previous event will then be reset to zero before the memory strobe reaches the memory module. In addition a veto logic inhibits flash ADC and memory strobes during the time an external busy signal (NIM) is applied to a veto input.

All the strobes are complementary ECL pulses fed into 110 Ω flat cables. Four outputs provide NIM signals equivalent to the memory strobes. The transit time inside the shaper is 27 ns, but the peak-finding logic needs an additional 40 ns to provide the flash ADC strobe.

5.3 *The flash ADC module*

At the time the system was designed, such modules were not commercially available. A circuit based on the Advanced Micro Devices AM6688 4-bit quantizer IC was therefore developed. It has a 100 MHz sampling rate and a 5 ns maximum encode delay. As a very similar product is now manu-

factured by LeCroy (ECLine 4504), no detailed description is needed. A schematic layout of the circuit is given in Fig. 5. Four flash ADCs controlled by individual strobes are located in a single width CAMAC module. The strobing is done with the trailing edge of the strobe input signal. The outputs of each flash ADC are complementary ECL signals giving a 4-bit digital word and an overflow bit into a flat cable bus. When an overflow occurs in a flash ADC, a preset manual switch sets each of the 4 bits of the digital word to one. The encoded output and overflow lines can also be read by CAMAC (flash ADC words). The total transit time is 15 ns.

The dynamic range is defined by two reference voltages, V_{low} and V_{high} , each one set by a 8-bit DAC through CAMAC between -2.55 V and $+2.55$ V. In the standard operating mode, V_{low} is set to 0 V, V_{high} is positive and the strobe is timed on the maximum of the bipolar pulse issued by the shaper. Since the shaper is an integrator, the flash ADC digitizes the charge. In test mode, a F25 CAMAC command generates a strobe which results, with 0 V at the input and with a suitable choice of negative V_{low} and positive V_{high} , in a specific pattern of the 4 output bits. As the outputs give DC levels and as the commands F25A0 to F25A3 address the four flash ADCs successively, it is possible to simulate any configuration of the 16 output lines. This provides a test facility for the flash ADCs themselves and for the look-up table connected to them.

5.4 The memory module

The memory module is based on ECL technology. It is a triple width CAMAC unit addressed through the middle board. A schematic layout of the circuit is given in Fig. 6. The RAM is located on the first board (three layer board) and uses 16 Fujitsu MB7072E chips, 256x4 bits with an access time of 12 ns. The first board also contains the input line receivers, the address multiplexers and latches, and the partial "ORs" of the memory matrix rows. The CAMAC section itself is located on the middle board. The different commands allow the writing of a start address, the writing/readout of the memory data with auto-increment of the address and the disable/enable of the external inputs. The middle board also contains the strobe generators, the partial "ORs" of the memory matrix columns, the overall "OR" logic and the individual memory outputs from the first two memory arrays. Only the overall

"OR" logic and the individual memory outputs from the two last memory arrays are situated on the third board.

The transit time between the input strobe and the different outputs is 30 ns. All the outputs provide MBNIM [3] signals except the overall "OR" signals (quadrant trigger signals) which are NIM.

5.5 The pulse generator system

The pulse generator system (Fig. 7) consists of a pulse generator module feeding four outputs, each of which is connected to a demultiplexer (one per quadrant) to select which of the eight adders is to be tested. The system can be controlled either manually or via CAMAC through an interface module.

The interface module is a single width CAMAC unit connected to the pulse generator module by a multiconductor cable. It allows selection of the charge of the test pulse, defined by a 12-bit DAC, and the address for the demultiplexers.

Each demultiplexer consists of a decoder and eight relay switches contained in a single width NIM module.

The pulse generator module is contained in a double width NIM module. It has visual displays and the switches necessary for manual control, four outputs for the pulses and four outputs to send the address to each demultiplexer. Photomultiplier dynode pulses are simulated by the following system: The DC level supplied by the 12-bit DAC (0 to +12 V) loads a 5.5 ns open coaxial cable through a high impedance (220 k Ω). An extremely fast drop of the impedance is produced by closing a mercury relay and the open circuit cable shapes a 11 ns FWHM positive pulse with a slew rate better than 15 V/ns. A small integration capacitor (4.7 pF) is added to the four outputs to lengthen the tail of the pulses making them similar to dynode pulses. As the timing of the pulse depends on the jitter of a mercury relay, a synchronisation circuit produces a trigger signal (NIM). A similar circuit is also contained in the generator module to produce negative pulses.

6. Performance, software filter and monitoring

In operation to date, triggers with p_T ranging from 1.1 to 4 GeV/c and with an energy balance requirement $|E_y - E_z|/(E_y + E_z) < 70\%$ have been used. Fig. 8 shows the transverse energy distribution inside triggered cells for different p_T thresholds after pattern recognition and shower reconstruction in the calorimeter and illustrates the sharpness of the p_T cut. A comparison is made with a "target interaction" trigger, where no information from the calorimeter is used (highest set of data points). Fig. 9 shows the distribution of the highest p_T electromagnetic shower of each event for the same trigger conditions as in Fig. 8. With a 280 GeV/c beam of $2 \times 10^7 \pi^-$ per 1.6 s effective burst and after coincidence with target interaction logic, a 3 GeV/c p_T trigger threshold (defined at 50% efficiency point) has a typical rate of 100 events/burst for the full calorimeter. The overall decision time between the input of the shaper and the "OR" output of the memory module is 120 ns (225 ns with the adder, the fast cable and the cables from the photomultipliers).

The 16 outputs of the memory chip matrix, which correspond to the pattern of the firing calorimeter trigger cells, are recorded for each quadrant and each trigger type. This information is then decoded by a fast front end microprocessor (MICE) [4] and combined with photomultiplier ADC data in order to perform a second filter. This second filter uses a fixed point instruction program associating the highest ADC cluster in Y and Z inside the firing trigger cells, and calculates an approximate p_T and energy balance in about 10 ms. It can be understood as a simulation of the hardware trigger after subdivision of the trigger cells in small squares of typically $3 \times 3 \text{ cm}^2$. As p_T is calculated on individual showers instead of being measured on the full energy deposited inside a trigger cell, it allows a steeper p_T cut to be made. With a p_T threshold in MICE set at half the hardware trigger threshold, a 50% data reduction is obtained [5]. Moreover, by using the information from the hardware trigger, multiple on-line and off-line checks can also be performed.

The trigger system is completely computer-controlled (through CAMAC) which allows not only the loading of the memories with the trigger conditions, but also the setting of the peak-finding logic discriminators, of the first level logic discriminators and of the range of all the flash ADCs. Furthermore, all functions of the electronics can be checked using the computer to inject calibrated charges

into the adders, or to drive the flash ADC built-in test facility. Comprehensive programs have been developed and used during the construction and the debugging of the electronics, as well as quick checking programs for data acquisition periods. In particular, a set of programs checks the level of all discriminators and tests the functioning of the flash ADCs by increasing step by step the 12-bit DAC of the pulse generator and reading back the discriminator status words and the flash ADC words. Linear fits are performed, slopes, pedestals, χ^2 s and DAC pulser values at which a given flash ADC step is reached are printed out. This last test allows a precise tuning of the amplification of the 32 adder-shaper-flash ADC chains ($\sigma = 2\%$) as well as time-stability controls. Other programs generate various memory address configurations through the flash ADC test device, read back the memory outputs and compare them to a simulated trigger table to detect memory module faults. With 5000 hours of operation, the trigger system has demonstrated a high reliability (only a single minor component failure).

7. Conclusion

The trigger system described here efficiently detects high p_T electromagnetic showers interacting in a large orthogonal readout calorimeter. This system works like a fast (120 ns) hardwired pattern recognition system. It is completely computer-controlled and has proved to be very reliable.

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FIG. 1

FIG. 2

FIG. 6

FIG. 7

FIG. 8

FIG. 9