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A Fast Cluster-Finder For The Fermilab Collider Detector Jet Trigger

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ABSTRACT

A general circuit has been designed for finding clusters in arrays of arbitrary dimension and regularity. A cluster is defined to be a contiguous group of elements of an array each containing logical "true" signals, surrounded by elements of the array containing logical "false" signals. This circuit has been adapted to the particular geometry of the Collider Detector Facility (CDF) to find clusters of energy in a two-dimensional rectangular array of calorimetry. The performance of the circuit has been studied in this application using monte carlo simulation.

INTRODUCTION

The CDF group is currently designing and constructing a general purpose detector that will be located at the B0 interaction region of the Fermilab pp collider.[1] There, beginning in 1984, it will observe proton-antiproton interactions at center-of-mass energies of up to 2000 GeV. An isometric view of the main components of the detector is shown in Fig. 1.

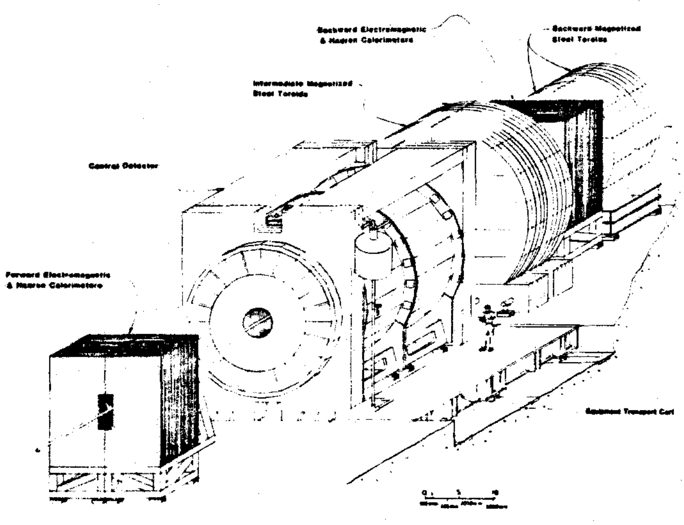

Fig. 1. The CDF Detector.

The 3 components (Forward, Central, and Backward) cover a solid angle of 2<θ<178, 0°<φ<360°, where θ is the polar angle with respect to the proton direction, and φ is the azmuthal angle.
An important physics goal of the CDF detector is the observation of very high energy jets of particles. Jets have been observed in hadron-hadron and lepton-lepton interactions and are thought to be manifestations of interactions between underlying fundamental particles (quarks and gluons). Hence, the study of jets yields information about the basic constituents of matter. At energies of 2000 GeV, the CDF detector will have the unique opportunity of observing jets with momentum transfers of 100-400 GeV/c. To aid in this detailed study of jets, the detector has been designed with two layers of calorimetry (electromagnetic and hadronic), each covering the solid angle 2°<θ<178°. For ease in triggering and data analysis, the layers of calorimetry are in "projective towers", each tower measuring energy flow in a definite region of solid angle. In order to be sensitive to the substructure of jets, the region of solid angle that each tower covers has been chosen to be small.
The θ-φ granularity of the calorimetry arrays is shown in Fig. 2.

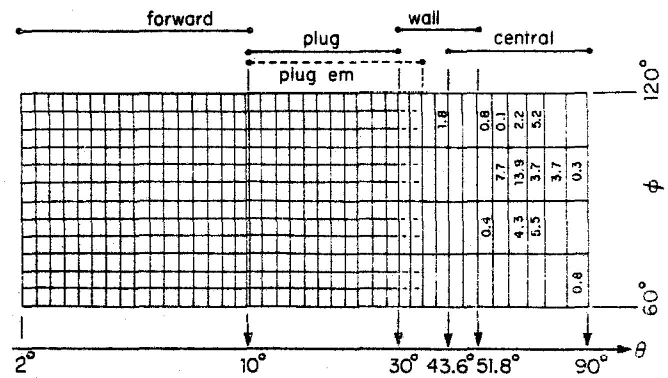

Fig. 2. θ-φ granularity of a section of the calorimetry array.

The numbers in Fig. 2 represent the energy deposited in GeV in the individual calorimetry towers for a typical 50 GeV jet.[2] An important feature is that the energy of a jet flows into many calorimetry towers. When triggering on jet events, one must somehow overcome this property of energy-sharing. To solve this problem, we have designed a cluster-finding module which groups energies deposited in the calorimetry array into clusters. In its design, we were guided by the requirements that: it should be very fast (the order of 1 to 2 μs per event) so deadtime due to the trigger is kept to a minimum; it should accurately reconstruct the energy of a jet; and it should be sensitive to the detailed topology of energy flow in an event (for example, be able to discern between 2- and 3-jet events.)

CIRCUIT

A cluster is defined to be a contiguous group of calorimetry towers each with deposited energy above some arbitrary threshold, surrounded by towers with no energy above threshold. From Fig. 2, we see that in the region 2°<θ<178°, there are 78 divisions in θ, and 24 divisions in φ. (For trigger purposes, towers in the plug and forward regions are

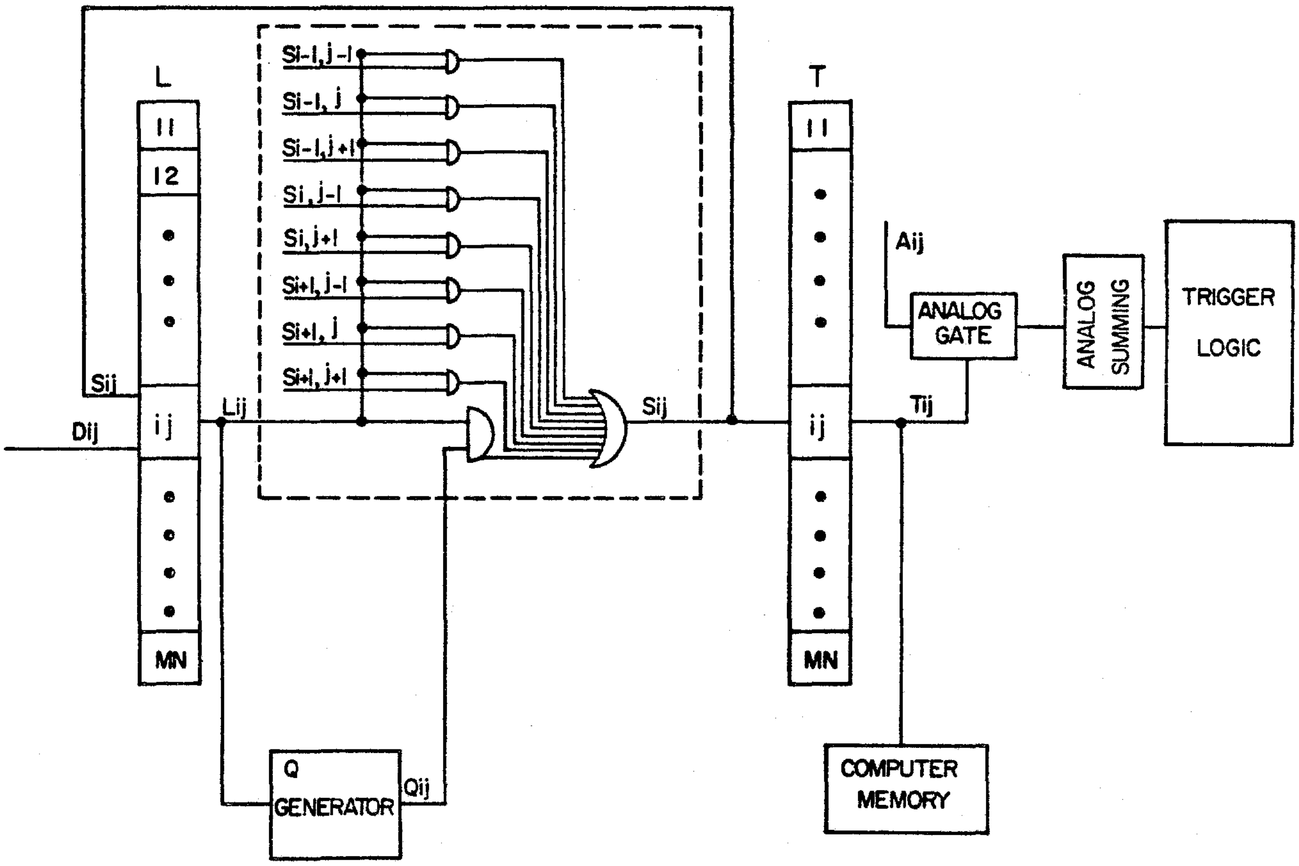

Fig. 3. The cluster-finding circuit.

summed 3 at-a-time to have the same ϕ segmentation as in the central and wall regions.) Therefore, the CDF electromagnetic and hadronic calorimetry can be thought of as rectangular arrays in the θ-ϕ plane, each array being 78 (= N) by 24 (= M). Each tower can be specified by 2 indices: a θ index, and a ϕ index. Because of the rectangular nature of the calorimetry arrays, each tower has eight nearest neighbors. From each tower, two signals are available: D_{ij}, a logical signal indicating deposited energy above threshold; and A_{ij}, an analog signal proportional to the energy. The circuit (shown in Fig. 3) works as follows:

1. D_{ij} are fed into latch register L.

2. The output levels of register L (L_{ij}) are input into N * M identical circuits (indicated by a dotted box in Fig. 3) and sent to a priority encoder-decoder (Q generator). The purpose of the Q generator is to select arbitrarily one of the hit towers. We note that the circuit inside the dotted box can be constructed using a single commercially available programmable logic array.[3] For the sake of definity, suppose that there is a cluster located in towers n-1,m-1; n,m; and n+1,m+1;(that is, $L_{n-1,m-1}$, L_{nm} , and $L_{n+1,m+1}$ are true) and that the Q generator has selected tower n-1,m-1 (line $Q_{n-1,m-1}$ of the Q bus is logical "true", the others are "false"). The Q generator addressing circuit n-1,m-1 causes $S_{n-1,m-1}$ to become true.

$S_{n-1,m-1}$ is fanned out to the circuits of the eight neighbors of tower n-1,m-1, and in particular, to the circuit of tower nm. Since L_{nm} is true, S_{nm} becomes true. Again S_{nm} is fanned out to the eight neighbors of tower nm, and the process repeats. After a settling time (100-200 ns), all towers in the cluster including tower n-1,m-1 will have their S lines in the logical true state. In other words, by addressing one hit tower in a cluster, all hit towers in that cluster are found.

3. The S_{ij} are clocked into the T register and, at the same time, reset their respective channels of the L register, deleting the previously found cluster (For definity, call that cluster C_1).

4. While the Q generator selects a hit element of the next cluster, the T register drives analog gates allowing the A_{ij} for

towers in cluster C_1 to be summed.

5. The T register information about cluster C_1 is written into a memory, so additional computation can be done at a later stage.

Steps 2 through 5 are repeated until all clusters have been found. At this point, the contents of the L register will be identically zero. We note that when all clusters have been found, the number of clusters found will equal the actual number of clusters in the event, and that the sum of energies of the clusters will equal the total energy of the event. (i.e. there is no multiple counting of clusters or energy.) The time required to find all clusters in an event is estimated to be

$$T \approx 300ns + n*(50ns + 120ns + 60ns) + 150ns$$

for n clusters. 300 ns is the time required for D_{ij} to reach the cluster-finder after the event. 50 ns is required by the Q generator to select a hit channel. 120 ns is required for settling time of the S_{ij}. (That time assumes typically 3 transits of an TTL programmable logic array.) 60 more nanoseconds are required to verify that the S_{ij} have indeed settled (that the full cluster has been found). 150 ns is required to form the analog sum of the A_{ij} for a cluster.

Since clusters are found in parallel with analog sums, only the last cluster contributes to the total time. These times indicate that a typical event with less than 5 or 6 clusters can be completely analysed in less than 2 µs. At this point we note that it is straight-forward to modify the above circuit for different geometries. Since the meaning of nearest neighbor is well-defined, cluster-finders for arrays of arbitrary order can be constructed. Needless to say, cluster-finders for regular arrays will be easier to build. For regular arrays other than a 2-dimensional rectangular array, the number of neighbors a given element will have varies. For example, the elements of a linear array have only 2 nearest neighbors, while the elements of a 3-dimensional array of rectangular solids have 26 nearest neighbors.

The cluster-finder described above finds all clusters in an event, each with its associated energy, and its hit pattern in the calorimetry array. In principle, 2 such devices can be built, finding independently clusters in the electromagnetic and hadronic calorimetry. However, correlated information about the clusters is interesting. For example, the signal of an electron is characterized by a very large ratio of the energy deposited in the electromagnetic calorimetry compared to the energy deposited in the hadronic calorimetry. A simple modification of the circuit shown in Fig. 3 allows such correlated information to be obtained.
Hit bits from the electromagnetic and hadronic calorimetry are "or" ed together before going into the L register. Clusters are found as before.

Finally, however, cluster energies are found independently for electromagnetic and hadronic clusters. This circuit is shown in Fig. 4.

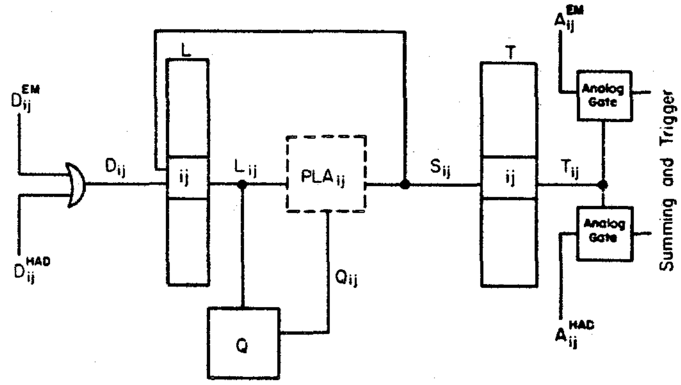

Fig. 4. A circuit that correlates hadronic and electromagnetic cluster-energies.

The performance of this circuit relies on the assumption that there is a reasonably strong overlapping of towers involved in the electromagnetic and hadronic showers produced by a particle or jet. (Obviously, a jet that showers in the hadronic calorimetry must have passed through the electromagnetic calorimetry in front.) In that case, the D^{EM}_{ij} are approximately the same as the D^{HAD}_{ij}, and "or" ing them together does not drastically affect the shape or energy of the clusters found. (Monte carlo simulations show that this assumption is correct.)

Simulated Performance

The cluster-finding algorithm was studied using a simulation of the CDF calorimetry which included effects of transverse and lateral shower development and energy resolution.[4] In the results that follow, energy deposition in calorimetry modules have been weighted by sinθ of the angle from the p direction to the center of the module. In this way clusters of E_T, energy transverse to the beam, were found. For most of the results that follow, a threshold of $E_{Tmin} = 0.5$ GeV transverse energy per tower has been used.

Monte carlo events were created by combining Field-Feynman jets[2] (with internal transverse momentum 0.7 GeV) of varying E_T and θ with beam jets. (The beam jets are products of the spectator quarks of the p and p.)

Fig. 5 shows the ratio of the E_T of the cluster found by the algorithm to the E_T of the incident jet for events with jets of E_T = 30, 50, and 70 GeV. We note that as E_T increases (the jet becomes more collimated), the ability of the algorithm to accurately reconstruct E_T improves. In addition, we note that the peaks of the distributions are at $E_T^{Cluster}/E_T^{Jet}$ somewhat lower than 1. This

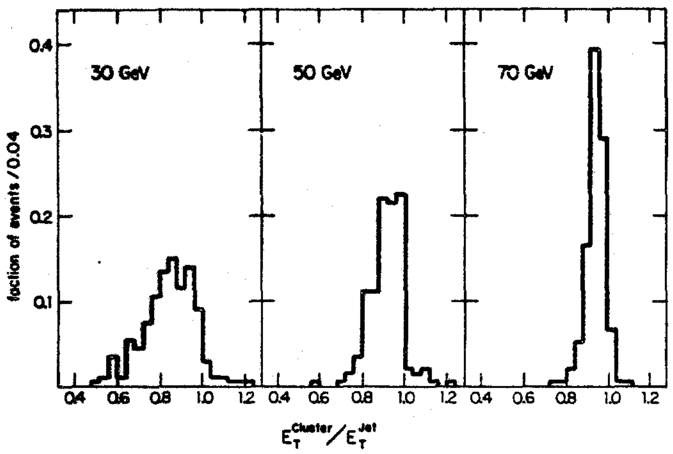

Fig. 5. E_T found by the cluster-finder divided by the E_T of the incident jet for jets of E_T = 30, 50, and 70 GeV.

primarily reflects the failure of the algorithm to correctly associate energy from the particles that are at large angles to the jet core. Again from Fig. 5, we see that the FWHM of reconstructed 50 GeV jets is 6 GeV.

As pointed out earlier, the shower development for electrons is very different from that of jets. Fig. 6 shows the ratio of hadronic to electromagnetic cluster E_T (H/E) for both 20 GeV electrons and jets. The dissimilarity between the two allows the possibility of using this ratio in a fast electron trigger. If we require H/E < 0.05, 95% of the jets are rejected while losing only 2% of the electrons.

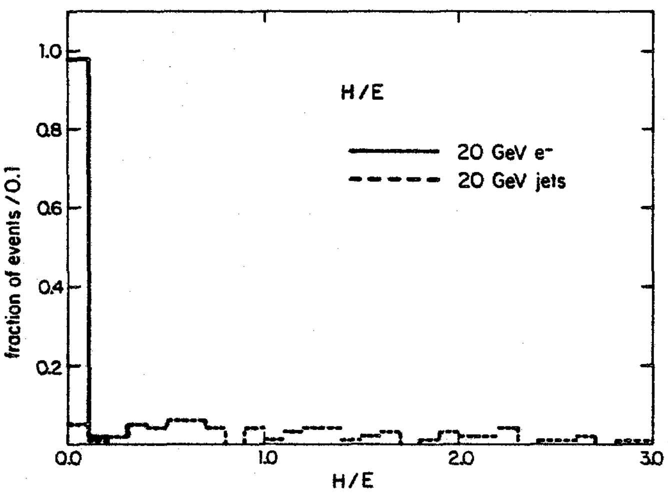

Fig. 6. H/E for 20 GeV electrons and jets.

As well as studying the energy resolving characteristics of the algorithm, we are interested in its ability to separate 2 jets at small angles from each other into 2 clusters. Fig. 7 shows the probability of separating the 2 jets for 50 GeV jets at θ = 90° as a function of the opening angle between the two. Using E_{Tmin} = 5 GeV, the algorithm is 100% efficient for angular separations greater than 45°. The probability of separation falls to 0 at an angle of about 20°. This effect is due to the calorimetry segmentation of 15 in ϕ.

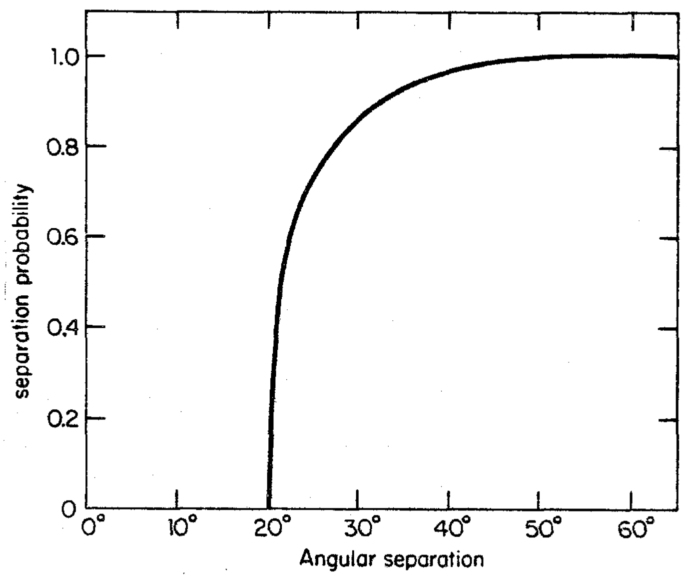

Fig. 7. Separation probability vs. opening angle between the two jet cores for 50 GeV E_T jets.

Summary

In conclusion, we have designed a circuit that can quickly find clusters of energy in a two-dimensional array of calorimetry. The circuit is easily modified for arrays of different geometry or dimension. The great advantage it has in the two-dimensional case of 8 nearest neighbors is that the basic logic per channel can be contained in a single integrated circuit.

*Operated by Universities Research Association under contract with the Department of Energy.

References and Footnotes

1. Design Report for the Fermilab Collider Detector Facility, CDF 111.

2. R. D. Field and R. P. Feynman, Nucl. Phys. B136 (1978) 1

3. For example, the Monolithic Memories PAL Series 20 programmable logic arrays.

4. J. Yoh, private communications.