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Pattern Comparator Trigger (PACT) for the Muon System of the CMS Experiment

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Abstract

The general scheme for the fast, pipelined first level trigger on high p_t muons in the CMS detector at LHC is presented. The prototype PACT system was tested in the high momentum muon beams in the RD5 experiment during 1993/94 runs. The obtained efficiency curves are shown.

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Introduction

In the present paper we describe the Pattern Comparator Trigger (PACT) processor designed for the Compact Muon Solenoid (CMS) detector [1, 2]. In the first section we introduce the general idea of the CMS muon trigger. The second one is devoted to the description of the PACT processor itself. Tests of the first PACT prototype are presented in section 3. Finally, the last section contains plans for the near future.

1 CMS muon trigger

Triggering is a crucial point at the Large Hadron Collider planned to be built at CERN (Geneva) at the beginning of the next century. At the highest design luminosity ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) a crossing of two proton bunches occurs every 25 ns. During each bunch crossing 20 to 40 individual proton-proton collisions take place. This 40 MHz rate must be reduced by the first level trigger down to 10-100 kHz acceptable for higher levels.

One way of selecting interesting events is to look at high transverse momentum (p_t) muons. The bandwidth allowed for this channel is about 1-10 kHz and thus a reduction factor of 10^{-4} is required. The trigger should not introduce any dead time and it has to be able to examine every consecutive bunch crossing. The decision about each event should be taken in less than $3 \mu\text{s}$.

In the CMS muons are measured by the detectors placed in the return yoke of the 4T superconducting solenoidal magnet. The detectors are arranged in four stations interleaved with magnetized iron providing the field up to 1.8 T. Muons are almost the only detectable particles being able to reach the muon stations. Other particles are stopped in the calorimeters placed inside the coil.

A large uncertainty in the estimate of physics rates, background and noise levels, as well as the possibility of surprises due to "new physics" forces us to make the trigger system very flexible with large safety margins. Therefore we envisage a possibility of having two complementary muon trigger systems: one based on dedicated fast detectors like Resistive Plate Chambers (RPC) [3, 4] and a second one using the muon chambers like Drift Tubes and Cathode Strip Chambers [1, 2]. In this paper we will concentrate on the first subsystem.

Let us introduce the cylindrical coordinate system with main axis z aligned with the proton beams. The solenoidal magnetic field bends tracks in the $r\varphi$ plane. In principle, knowing the vertex, two measuring planes after the coil giving a local track vector are enough to measure the momentum and apply a p_t cut. To deal with fluctuations due to multiple scattering and energy losses and to account for the geometrical inefficiencies we take advantage of having 4 muon stations and make use of 4 measuring planes (one per station). A four point pattern (see Fig. 1) is more redundant than the simple vector and gives a sharper cut. The above idea has to be slightly modified for muons with $p_t < 8 \text{ GeV}$ in the barrel ($|\eta| < 1$) because they are not able to reach outer muon stations. Therefore we place two triggering planes in the first and the second muon station and again use a four point pattern to make the p_t cut.

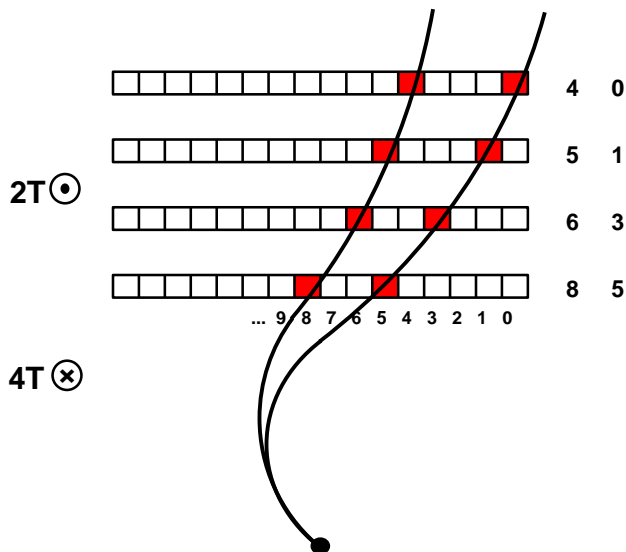


Figure 1: Four hit patterns created by muon tracks bent in magnetic field.

Resistive Plate Chambers are read out with 20-90 cm long strips. A particle passing through the detector crosses muon stations, hitting the RPC strips on its way. In the absence of energy loss and multiple scattering there will be a one to one correspondence between the pattern of hits and the muon transverse momentum. Energy loss and multiple scattering smear this out, generating a set of hit patterns for each value of p_t . The sets of valid patterns change with pseudorapidity η . They are practically η independent in the barrel region, but vary in the forward region [6]. The sets of patterns for various transverse momenta are ordered i.e. a higher p_t set is a subset of a lower p_t set. This property allows us to establish the set of patterns for a given value of the threshold p_t^{cut} . Such a set can be loaded into a trigger processor. Then every observed track pattern is compared with the predefined patterns. A track gives a trigger if its pattern belongs to the set of valid patterns. More details about the algorithm and results of its simulation can be found in [6].

2 Pattern Comparator Trigger (PACT)

2.1 Segmentation

The RPC trigger of CMS is foreseen to cover an area up to $\eta = 2.1$ with a possibility of upgrade up to $\eta = 2.45$. The information from all triggering planes within a certain region of the detector is first processed by the segment trigger processor. The main function of the segment processor is to recognize a muon and measure its momentum. It is performed by the Pattern Comparator (PAC) described in the next section. Presently the segment is assumed to be 1 strip long and 8 strips wide and thus it covers 2.5 degrees in φ and ~ 0.1 unit in η . These numbers determine double muon resolution of the trigger, i.e. two muons within the same segment will be seen as one. Therefore the segmentation is still a subject of optimization and an impact of the choice is being studied with the simulation of interesting physics channels.

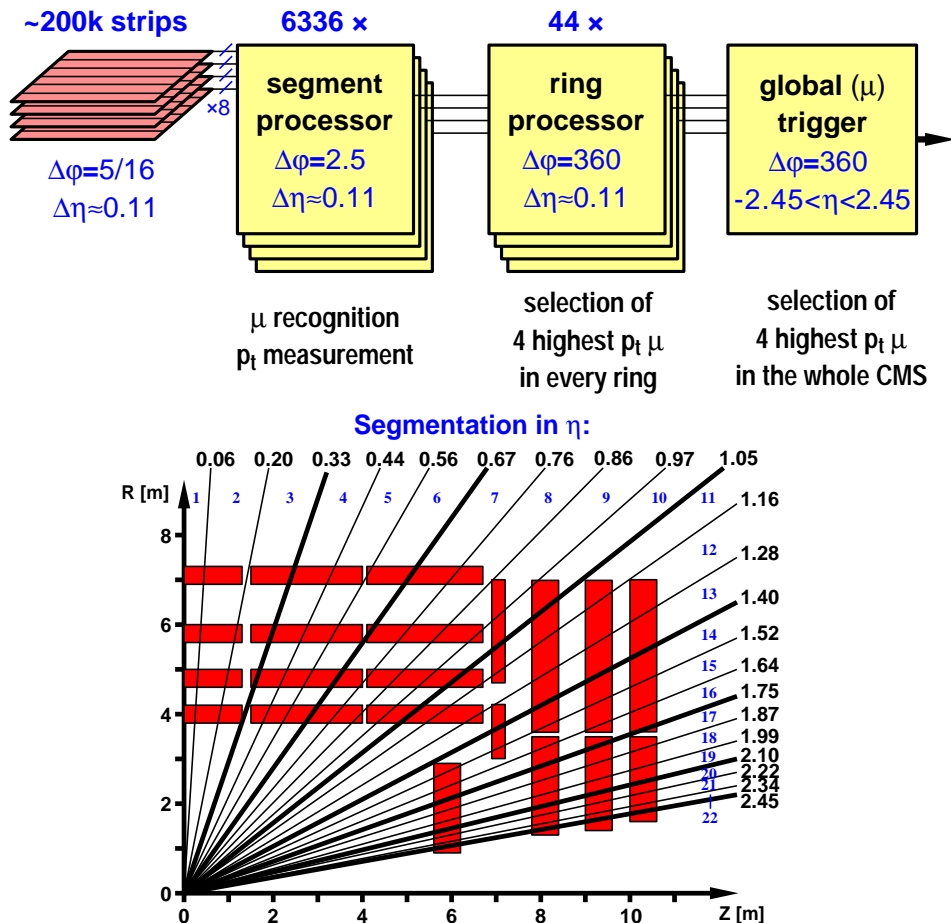


Figure 2: CMS muon trigger segmentation. Rectangles represent muon stations containing RPC chambers.

Figure 3: Schematic drawing of the CMS muon trigger.

They should be supported by general CMS services:

- timing distribution network,
- front-end bus and front-end driver - a connection to the CMS data acquisition system.

Special care will be needed to make this electronics error free and fully testable. We plan to use circuits equipped with boundary scan facility to perform functional tests of the system. All elements of our electronics in the main subdetector data stream will have a pipelined structure, i.e. the PACT will be dead time free.

Figure 4: Regional trigger and readout board.

2.4.1 Segment synchronization and pipeline memory block

The purpose of the synchronization block is to synchronize the signals coming from 4 different muon stations and to provide signals related to one specific bunch crossing. Since low momentum muons frequently cross segment boundaries certain part of the synchronized signals should be sent to the neighbouring TRB's.

The pipeline memory is used for:

- storage of the data during the time when the first level trigger decision (Accept signal) is elaborated,
- storage of the data corresponding to the bunch crossing accepted by the first level trigger (derandomizer buffer); the depth of the derandomizer has to be at least 5.

2.4.2 Pattern Comparator (PAC)

This is the main part of TRB. The pattern comparator provides the information about the highest momentum muon crossing the segment area. The output of the processor will be a 6 bit code of the muon momentum. The most significant bit defines the sign of the muon. Code "0" means that there was no muon in the segment (or that its momentum was below the lowest threshold).

Pattern comparator uses as its inputs data from the segment synchronization processor as well as the synchronized data coming into the segment from neighbour TRB's. Pattern comparator contains the pattern recognition part followed by the momentum definition part followed by the encoder (see Fig. 5).

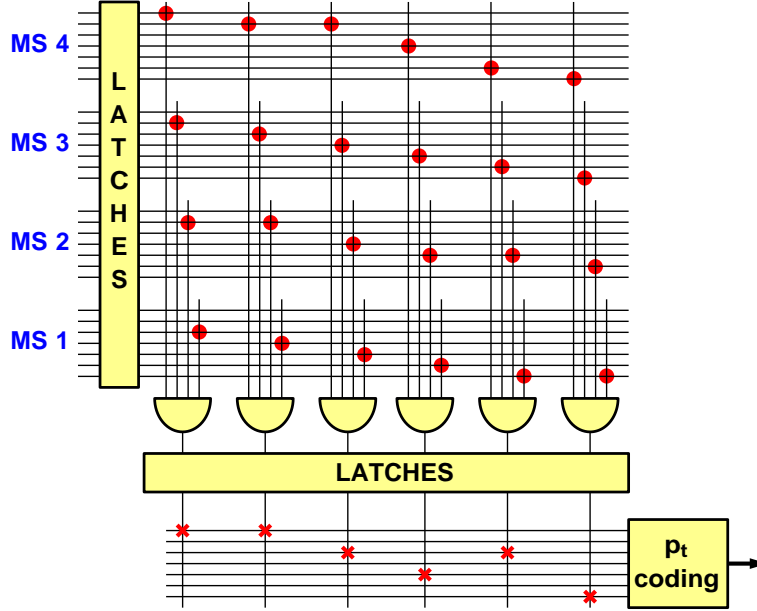


Figure 5: Segment trigger processor.

The first part consists of 4-fold coincidences, one input for each muon station. Each coincidence corresponds to one pattern of muon track found in 4 muon stations. The second part performs the logical OR'ing of the coincidences to group together the patterns corresponding to the same momentum. The last part of the circuit forms the 6-bit output code.

All these operations are performed by programmable devices, to allow the change of the track patterns and corresponding p_t cuts. If necessary, a dead strip will be replaced by logical "1" to avoid efficiency losses.

Large multiple scattering and energy losses at low momenta cause large fluctuations of track shapes (see Fig. 6). This leads to a rapid increase in the number of valid patterns (Fig. 7). On the other hand low p_t tracks are more bent and high granularity of the detectors is not needed. Taking this into account one can reduce the number of patterns to be fed into the processor by logical OR'ing a few neighbouring strips for low p_t^{cut} . In other words the logical strip size can be increased.

Patterns will be given first by the simulation of the muon tracks in the detector and of detector response. Later they will be updated according to real muon tracks reconstructed with the help of precise muon chambers. Information about dead and noisy strips will be also included in the patterns. The downloading of the configuration data to the trigger processor will be performed by the control processor through a serial link.

2.4.3 Segment control and test block

The control and test block serves as the interface to the CMS timing distribution module and will provide the different clocks for TRB elements. It provides an interface to the serial link used for downloading data to the programmable parts of TRB and to control execution of internal test procedures. These functions could be based on IEEE1491.1 boundary scan standard. It will allow us to establish the status of the segment module electronics and to reprogram the module if necessary. The task of system calibration should be also controlled by this unit.

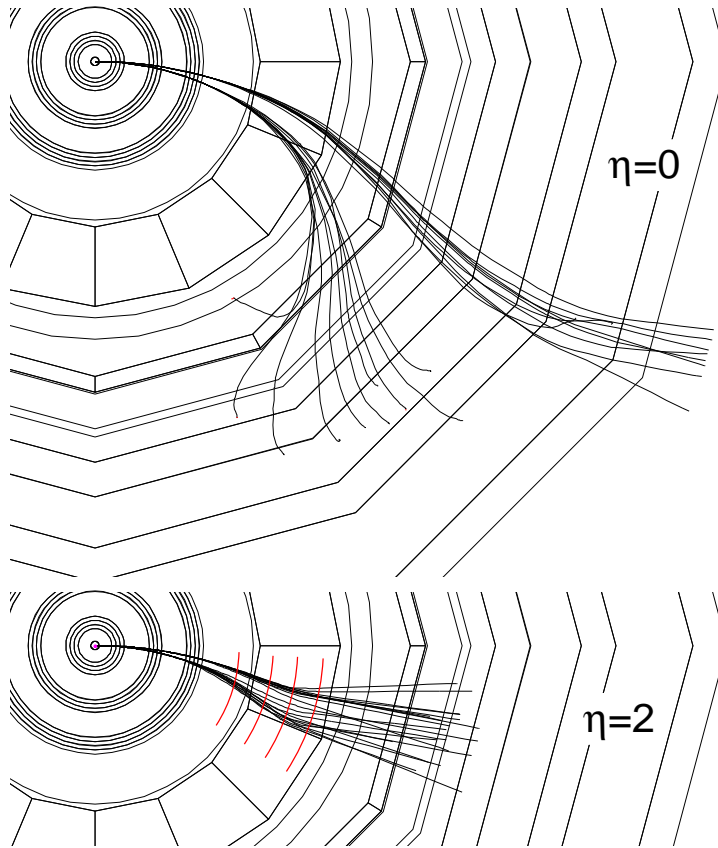


Figure 6: Examples of the muon tracks in the CMS detector. Two families of tracks have $p_t = 4$ and 6 GeV respectively.

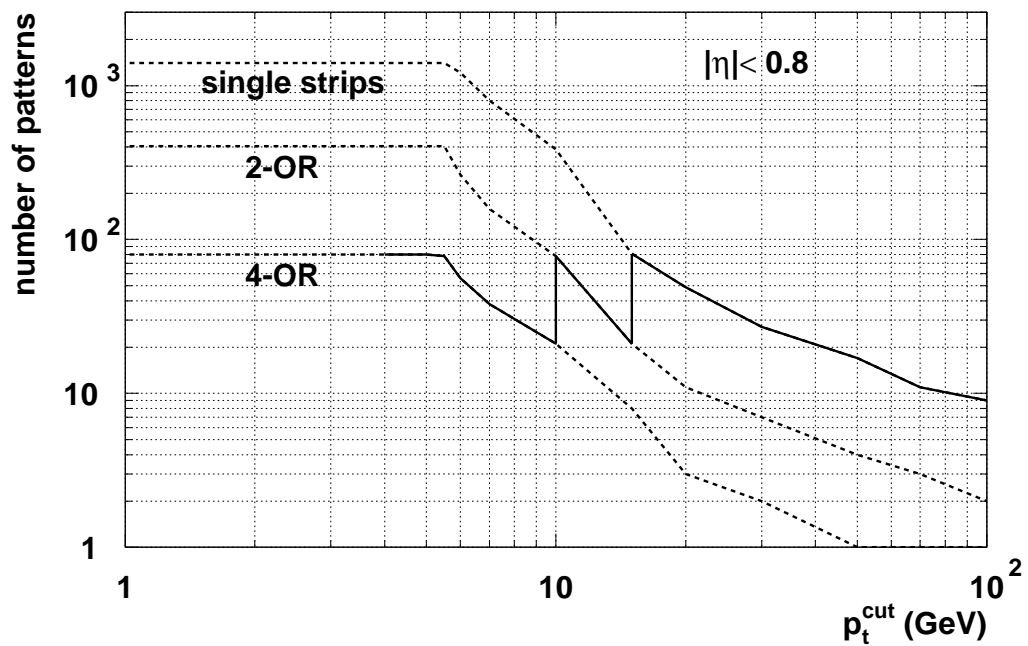


Figure 7: Number of patterns per strip for single and or'ed strips.

2.5 Sorting tree

The basic goal of the sorting tree is to reduce the amount of data to be sent to the global trigger. This function will be performed by a tree of dedicated VLSI sorter circuits each of which will find the four highest p_t muons out of sixteen.

3 PACT tests in RD5

A prototype of the PAC was built and tested in the framework of the RD5 experiment at CERN with the muon beam [7]. The magnetic field configuration of RD5 closely resembles that of CMS making it a good choice for testing the trigger processor performance. The RD5 is equipped with twelve planes of $2 \times 2 \text{ m}^2$ RPC chambers with 3 cm wide horizontal strips. Four of these chambers corresponding to four CMS muon stations were used in this test. The muon penetrated 144 cm of steel plates before arriving at the first RPC and then 60 cm of iron to each of the subsequent chambers. The readout by the trigger processor covered 18, 20, 24 and 30 strips from consecutive chambers which was sufficient for the current study (Fig. 8).

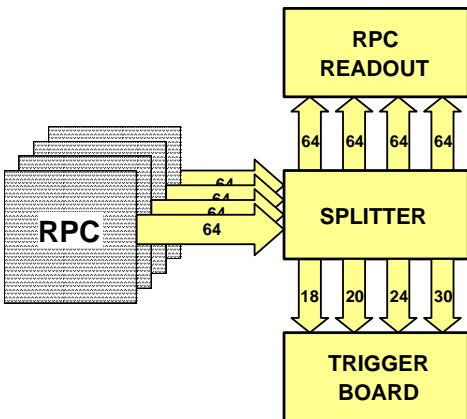


Figure 8: Segment trigger processor in RD5.

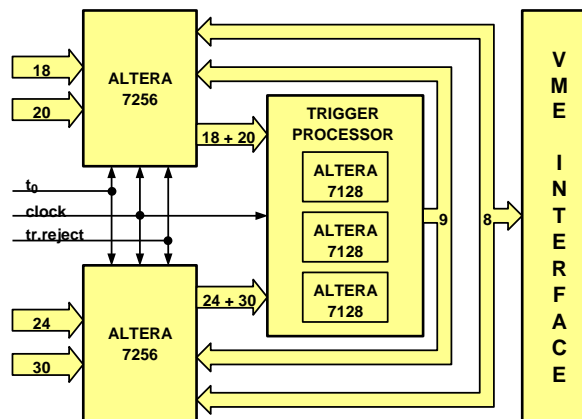


Figure 9: Segment trigger processor VME board.

The processor itself was built using three programmable ALTERA 7128 chips, each of them corresponding to a single PAC (Fig. 9). Two more ALTERA units were used to feed the data into the PAC's and to handle communication with the VME. The signals coming from the chambers passed through a splitter module enabling simultaneous access by the standard RD5 readout and the trigger processor itself. The processing of an event was initiated by the RD5 trigger signal corresponding to the passage of a beam particle through a set of scintillation counters. The results were ready after 4 VME clock periods and were then read out.

The trigger processor was loaded with patterns corresponding to the different momentum cuts. Each pattern consisted of four strip numbers from consecutive chambers. The patterns used corresponded to the momentum intervals: 10-20, 20-30, 30-50, 50-100, and above 100 GeV. The number of patterns for each interval was equal to 15, 6, 4, 3, 2 and 4 per strip, respectively. The patterns were selected in such a way as to keep at least 99% of tracks at each energy.

In the present analysis we restricted ourselves to events where in each chamber we had at least one strip hit in the region read by the trigger processor. In other words we assumed the chambers to have 100% efficiency.

Fig. 10 shows the trigger efficiency as a function of the beam momentum for various thresholds. It can be seen that the selectivity of the trigger (i.e. the steepness of the curve) is good.

In the RPC's used in the test it often happens that a single muon crossing a chamber produces signal in more than one strip. In Fig. 11 we show the fraction of events at a given strip multiplicity, defined here as the total number of hit strips in all four chambers. The behaviour of the trigger efficiency depends on the multiplicity of strips: the larger the multiplicity, the higher is the momentum value obtained by the trigger processor since more strip combinations are available and more straight combinations of hits are likely to be present. Fig. 12 shows the trigger efficiency for the strip multiplicity to be less or equal to a given cut at a given threshold value for various beam momenta. The efficiency shown in those plots is calculated relative to the number of events at a given multiplicity cut.

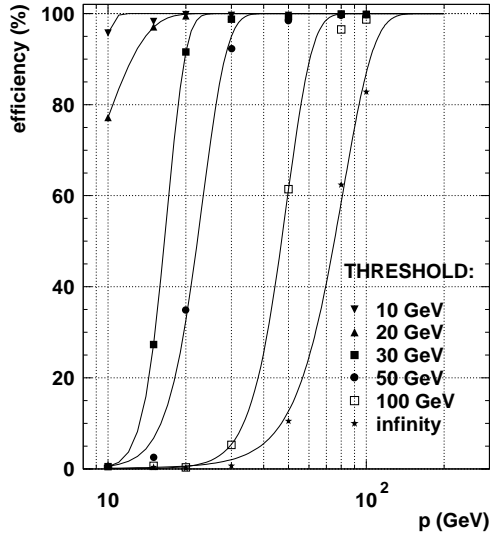


Figure 10: Trigger efficiency vs beam momentum. The curves are drawn to guide the eye.

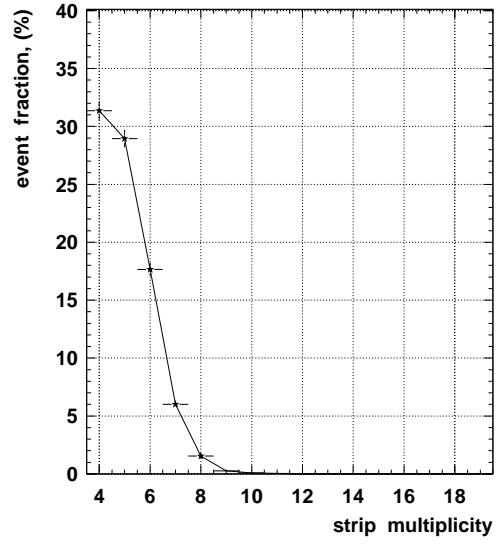


Figure 11: Fraction of events as a function of the strip multiplicity.

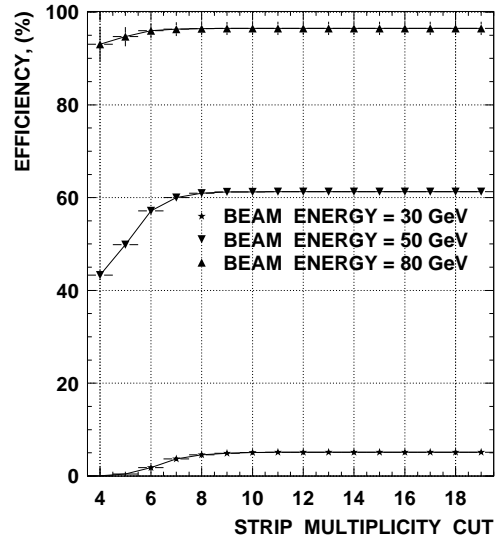
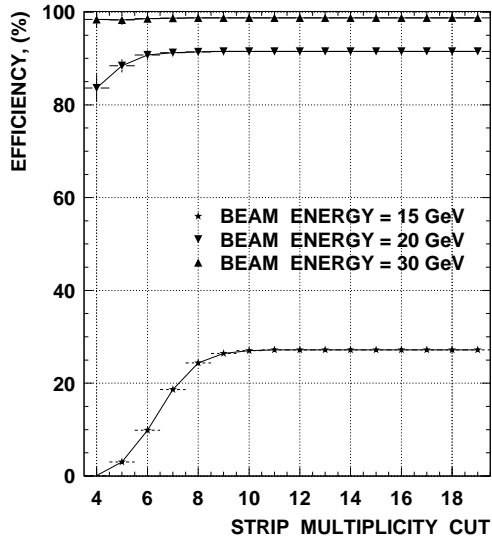


Figure 12: Trigger efficiency for threshold 30 GeV (left graph) and 100 GeV (right graph) at various beam momenta vs. total multiplicity less or equal to a given cut.

The following facts can be observed:

- The trigger efficiency for the beam momentum equal to the threshold value does not suffer any significant loss for small strip multiplicities.
- The probability to assign higher momentum value for lower beam momenta drops significantly with decreasing strip multiplicity.
- In order to have good trigger selectivity it is important to reduce the cluster size in the chambers without any important loss in the efficiency.

We also took data without the beam and found no triggers among 18500 events. This was expected, because the chamber noise was as low as 1 Hz/cm².

4 Plans for the future

A relatively large quantity of pattern comparators and sorters as well as their rather specific architecture suggest that developing dedicated ASICs will be more economic than using programmable FPGA devices like ALTERA or XILINX. The work on the VLSI implementations is going on [8, 9] and we expect the first prototype to be ready in mid 1995. Currently we are setting up a test bench to study performance and functionality of these chips and develop various procedures like synchronisation and time calibration, zero suppression and DAQ interface, programming and control, boundary scan and other testing procedures.

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References

- [1] *CMS Letter of Intent*, CERN/LHCC 92-3.
- [2] G. Wrochna, Nucl. Instr. Meth. A334 (1994) 98.
- [3] R. Santonico, R. Cardarelli, Nucl. Instr. Meth. 187 (1981) 377;
R. Cardarelli et.al., Nucl. Instr. Meth. A263 (1988) 20.
- [4] Gy. L. Bencze et.al., Nucl. Instr. Meth. A340 (1994) 466.
- [5] R. Cardarelli, A. Di Ciaccio and R. Santonico, Nucl. Instr. Meth. A333 (1993) 339;
Gy. L. Bencze et.al., *Test of Resistive Plate Chambers operating with low gas amplification at high intensity beams*, Preprint of "Tor Vergata" Rome University, ROM2F/94/11, March 21, 1994, to be published in Nucl. Instr. Meth. A.
- [6] M. Konecki, Warsaw University M.Sc. thesis, 1992, unpublished;
M. Konecki, J. Królikowski, and G. Wrochna, *Simulation study of the single muon, RPC based trigger for CMS*, CMS TN/92-39;
H. Czyrkowski et al., *RPC based CMS muon trigger - progress report*, CMS TN/93-111.
- [7] *Status Report of the RD5 Experiment*, CERN/DRDC 91-53, January 13, 1992;
Status Report of the RD5 Experiment, CERN/DRDC 93-49, January 5, 1994;
M. Aalste et al, Zeitschrift für Physics C 60, 1 (1993).
- [8] P. Gorodenski, F. Klefenz, and R. Männer, *VLSI implementation of the pattern comparator trigger*, talk given at the 29th CMS Collaboration Meeting, CERN, July 1994;
P. Gorodenski, F. Klefenz, R. Männer, *VLSI-Implementierung eines Musterkoinzidenz-Prozessors*, Proc. PARS Worksh., Potsdam, Germany, 1994 (in print).
- [9] M. Kudła and A. Ranieri, *CMS muon sorter*, talk given at the 29th CMS Collaboration Meeting, CERN, July 1994.