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The CHAOS Second Level Trigger. A Fast, Programmable ECL Trigger for a Magnetic Spectrometer using Multiwire Proportional Chambers.

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Abstract

A versatile second level trigger has been developed for the CHAOS facility at TRIUMF using fast ECLine trigger modules augmented by some specially constructed modules. It consists of a primary stage and two optional secondary stages. The primary track finding stage is capable of making a decision based on track vertex, polarity and momentum. The next stage is able to reject events based on the correlation between track momentum scattering angle. The third stage can make a cut on the sum of the momenta of two tracks. In addition there is an extra parallel stage that is responsible for ensuring that the beam particle has the correct incoming trajectory. All stages are programmable and, depending on experimental conditions and trigger configuration, usual rejection times are between 2 and 4 μ s.

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1. Introduction

The CHAOS (Canadian High Acceptance Orbit Spectrometer) facility is a charged particle magnetic spectrometer used for pion physics experiments at TRIUMF. It is based on a cylindrical dipole magnet that produces a vertical field of up to 1.6 T with less than 0.6% deviation from uniformity out to a radius of about 35 cm. CHAOS experiments make use of several targets including cryogenic and polarised targets. These are placed at the centre of the magnet and are accessed through a 12 cm wide open bore down the cylindrical axis. In order to be able to reconstruct the tracks of charged particles in the spectrometer there are four concentric cylindrical wire chambers surrounding the target. The outermost of these (WC4) is a vector drift chamber and is located outside the region of uniform magnetic field. Beyond WC4 is a ring of scintillation and lead-glass Čerenkov detectors used for particle identification and to determine event multiplicity. The layout of the CHAOS facility is shown in fig. 1. It is described in detail in reference [1] but a brief overview of the components necessary for an understanding of the second level trigger is given here.

The innermost two chambers (WC1 and WC2) are multi-wire proportional chambers with an anode wire spacing of $\frac{1}{2}^\circ$. There are cathode strips inclined to the anode wires by 30° on the inside surface of the outer wall of each chamber. These are situated every 1° . The struck anode wire numbers are read out using the LeCroy multiwire proportional counter operating system (PCOS III) and the magnitudes of the pulses induced on the cathodes are obtained using a bank of LeCroy 1882F FASTBUS ADC's. The PCOS systems for WC1 and WC2 are operated in cluster mode in order to optimise the resolution of these chambers. This means that the address of a cluster of struck wires is given to the nearest $\frac{1}{4}^\circ$. The width of each cluster is also present on the output and such words are identified by having the most significant bit set.

The third chamber (WC3) is at the edge of the region of uniform field. It is a thin drift chamber with 144 anode wires and four cathode readout strips per wire and has been described in a previous publication [2]. The anode wires are instrumented with TDC's and, for the purpose of making a rapid trigger decision, are also connected to a PCOS III system operated in cluster mode. The output addresses are thus in units of $\frac{5}{4}^\circ$. However, due to the large WC3 anode pitch, a hit near the centre of two wires may not fire both wires so the effective resolution of the PCOS readout is somewhat greater than $\frac{5}{4}^\circ$. WC3 is usually deadened in the region of the incoming and outgoing beam to avoid damaging the chamber by drawing excess current.

The first level of triggering is obtained from the scintillator-Čerenkov counter telescopes and is known as the CHAOS fast trigger (CFT) [3]. The decision is based upon the minimum number of particles (event multiplicity threshold) that produce a signal in the CFT blocks. The first level trigger rate is typically 3 kHz for a 3 MHz incident π^+ beam on 5 cm diameter liquid hydrogen target and with a multiplicity threshold of two detected particles. However, the maximum rate at which the data acquisition computer can read and write events with good efficiency is approximately 200 Hz. Therefore, in order to reduce the system dead-time and increase the fraction of interesting events recorded, a second level of triggering is needed. Also, as CHAOS was intended for several types of experiment, the second level trigger must be versatile enough to accommodate various trigger conditions.

2. Overview of the second level trigger

The second level trigger consists of several stages. It utilises the struck wire numbers from the proportional chambers (WC1, WC2, WC3). These data are available from the PCOS readout system within 200 ns of the first level trigger whereas it takes about 250 μ s for the ADC's to do their conversion. Note that in general there will be more than one cluster of struck wires for each chamber so there will be several combinations of the hits to be considered. Each combination of hits defines three angles $\theta_1, \theta_2, \theta_3$ at the known chamber radii. These three points uniquely define a circle whose radius is denoted by R with the coordinates of the centre denoted by (r_c, θ_c) . The corresponding track momentum is proportional to the radius of curvature and the distance of closest approach to the origin is given by

$$d = |r_c - R|$$

In addition, the polarity of the track, denoted by $\xi = \pm 1$, can be determined from θ_c and θ_2 assuming an outgoing particle. In particular, a track corresponding to a positively charged particle in a downward magnetic field has $\sin(\theta_c - \theta_2) > 0$. It is not possible to have $\sin(\theta_c - \theta_2) = 0$ as such tracks would never intersect both WC1 and WC3.

The second level trigger is constructed primarily from LeCroy ECLine trigger modules [4] which have a typical throughput time of about 60 ns and meet the flexibility requirements in that they are programmable via CAMAC. The basic decision-making module is the memory lookup unit (MLU). The input word to an MLU represents some physical quantity or combination of quantities and is treated as an address. The contents of that address are then presented on the output along with a ready (RDY) signal. The memory is normally filled by the user prior to use and represents the results of some calculation performed on all possible inputs. In addition to the commercially available LeCroy 2372 16-bit MLU's, two 21-bit MLU's were designed and constructed at TRIUMF to meet the word size requirements of the secondary stages. Also, a module consisting of sixteen edge-triggered single bit latches with a common reset was constructed at TRIUMF for use within the second level trigger.

The data available to the second level trigger are presented on an ECL bus in the form of PCOS addresses corresponding to the centroid of a cluster of struck wires. The WC1 and WC2 angles are in units of $\frac{1}{4}^\circ$ and so require eleven bits each to cover the full 360° . The angles from WC3 are in units of $\frac{5}{4}^\circ$ and hence require nine bits to encompass the full angular range. Thus each $\theta_1, \theta_2, \theta_3$ combination requires thirty-one bits to represent it completely. An MLU with this input word length is not available and so a method for reducing the data was designed.

3. Data reduction algorithm

The scheme for reducing the data to an input word size appropriate for existing MLU's makes use of the rotational symmetry of CHAOS. For a track defined by $(\theta_1, \theta_2, \theta_3)$ the coordinate system is rotated about the origin by θ_2 leading to

$$\begin{aligned}\theta_1 &\rightarrow \theta'_1 = \theta_1 - \theta_2 \\ \theta_2 &\rightarrow \theta'_2 = 0 \\ \theta_3 &\rightarrow \theta'_3 = \theta_3 - \theta_2\end{aligned}$$

These subtractions are performed in ECL using LeCroy 2378 Arithmetic Logic Units (ALU). The WC3 data must first be converted from units of $\frac{5}{4}^\circ$ to units of $\frac{1}{4}^\circ$ and hence will also require an eleven bit representation. The momentum, polarity and distance of closest approach of the track to the origin can be determined from θ'_1 and θ'_3 without loss of information. These two quantities can be represented in a total of twenty-four bits. Each requires eleven bits of data plus a sign bit due to the possibility of a negative angle from the subtraction.

The number of bits needed to specify the track can be reduced further by noting that there is a lower limit on the radius of curvature of a track that can be detected with CHAOS. Any track with a radius of curvature less than the limit would not reach WC4 and hence need not be considered by the second level trigger. In the rotated coordinate system ($\theta'_2 = 0$), a lower limit on the radius of curvature leads to upper bounds on the magnitudes of θ'_1 and θ'_3 . A convenient range for θ'_1 and θ'_3 is from -32° to 31.75° as this is well within the acceptance of the spectrometer. When constrained to lie in this range, θ'_1 and θ'_3 can be represented with eight bits each and so the data word size to the input of the final decision making MLU (MLU J) can be reduced to sixteen bits. A schematic representation of the reduction algorithm is shown in fig. 2.

4. The track finding stage

The first stage of the second level trigger is the track finding stage and is used for every experiment. All combinations of hits are tried until a good track is found, otherwise a reject decision is issued. The requirement of versatility necessitates that the definition of a good track is flexible. It is based on one or more of the following criteria:

- The distance of closest approach of the track to the origin must be within the target region, thus putting an upper limit on d .
- The momentum must be within a specified range (usually the momentum acceptance of the spectrometer).
- The track polarity must be as specified (positive, negative or either).

An implicit but powerful criterion is that a track must exist before these requirements can be tested.

The complete layout of the track finding stage is shown in fig. 3. The first task it performs is storing the ECL data from PCOS so that it can loop over all the possible input combinations. The LeCroy 2378 PCOS controllers for WC1 and WC2 are daisy chained so that θ_1 and θ_2 data are transferred on the same ECL bus to MLU B. Note that terminator words and words specifying the width of the cluster will not trigger the MLU B input as the bit that identifies these words is inverted into the enable (EN). The function of MLU B is to distinguish between WC1 and WC2 data and steer them to data stacks E and D respectively. This is achieved through the use of a feature of the LeCroy 2375 data stacks that allows them to only accept data with a preset combination of the three most significant bits. The θ_3 data are transferred from the WC3 PCOS controller to MLU A which converts them from units of $\frac{5}{4}^\circ$ to units of $\frac{1}{4}^\circ$ and passes them on to data stack C.

The θ_1 and θ_2 data are fed into ALU G which performs a subtraction giving θ'_1 in two's complement representation (twelve bits). This quantity is passed to MLU I which, if necessary, rotates the angle by 360° to bring it into the range of $0^\circ \pm 180^\circ$. If it is between -32° and 31.75° inclusive then the output is θ'_1 on the lower eight bits, otherwise the two most significant bits of the output are set indicating a rejection. The same series of operations is performed on θ_3 and θ_2 by ALU F and MLU H leading to θ'_3 in the same range or else the reject bits are set. A rejection from either MLU H or MLU I blocks processing at MLU J by disabling its input and also sends a NEXT pulse back to the data stacks. The NEXT pulse retrieves the next combinations of hits from the data stacks. Without a reject flag, the data are passed to MLU J which is preloaded with the result of the decision criteria for all possible combinations of the sixteen input bits representing θ'_1 and θ'_3 . If the combination satisfies the conditions then a GOOD TRACK pulse is produced and if not a NEXT pulse is produced.

4.1. Initiation and the looping sequence

The CHAOS second level trigger is initiated by the PCOS readout which is initiated by a first level trigger. Main processing is begun by the *All Data In* (ADI) signal which is constructed from the AND of the inverted BUSY signals from the two PCOS controllers signifying that both have finished transporting data through their ECL ports. The ADI signal arrives about 200 ns after the last data word. A REJECT pulse is issued immediately if there is not at least one of each of $\theta_1, \theta_2, \theta_3$. It is necessary to delay the main processing loops until the ADI signal so that the correct timing of the circuit is achieved. Processing is blocked at MLU's H and I until the ADI signal sets the data latch L1 to begin processing.

A $\theta_1, \theta_2, \theta_3$ combination can fail at either MLU H, MLU I or MLU J. When this happens a NEXT pulse is generated by inverting the data ready (RDY) output of the MLU, delaying it by the width of the pulse and taking the logical AND of this with the appropriate bit of the output that indicates failure. This procedure is necessary to convert the ready from level to a pulse. The NEXT pulse propagates through a series of OR gates to the read enable (RE) input of the data stacks. The WC1 data stack will only be strobed when the read overflow (ROF) of the WC3 stack is true, indicating that the last WC3 data word is present on the output. Similarly a new WC2 data word will only be issued when the ROF's from both the other two stacks are TRUE. Each data stack automatically loops back after the last word and so all combinations of $\theta_1, \theta_2, \theta_3$ are tried via a nested looping sequence with the WC3 data being the innermost loop. The WC1 data are the middle loop and the WC2 data comprise the outermost loop. When all three ROF's are TRUE the last combination is tried and latch L2 is set. If the final combination fails, the subsequently generated NEXT pulse becomes the REJECT pulse.

5. The momentum versus scattering angle cut

The results of the track finding stage can be used for one of two subsequent optional stages. The first of these performs a momentum versus scattering angle (θ_s) cut on single tracks passed by the first stage. This cut is important for the elastic scattering experiments. It enables a kinematic separation to be made between the π -p

elastic scattering events and those from elastic scattering off heavier nuclei such as helium, oxygen and carbon in a polarised target, for example. Fig. 4 illustrates the pion momentum versus scattering angle for elastic scattering from hydrogen, helium and carbon at an incident pion energy of 100 MeV. The separation at angles greater than about 50° is clearly seen. An upper limit on the momentum as a function of the scattering angle thus provides a valuable discrimination tool.

Note that the second level trigger receives only a fraction of the information available from CHAOS. In particular, the drift time information from chambers 3 and 4 is not available and so it cannot make a highly accurate determination of the momentum or scattering angle. Also, it does not reconstruct the incident beam track and so it makes the assumption that the interaction vertex within the target is approximately equal to the point of closest approach of the outgoing track to the origin. Neither does it determine if a track is that of a pion or another charged final state particle such as a proton. However, every good event can be tested for a momentum versus scattering angle correlation. All the information needed for this cut is contained in the three angles $\theta_1, \theta_2, \theta_3$ and so in principle the momentum versus scattering angle cut could be made in the track finding stage. However, the limitation on data word size necessitates that this be an extra stage.

This section makes use of the results from the primary track finding stage. The first bit of the MLU J output word is the GOOD TRACK bit. The next bit is used for the polarity and the other six bits for the momentum in constant increments between a predetermined minimum and maximum. The extra circuitry required for this stage is shown in fig. 5. The decision making module is the TRIUMF 21-bit MLU K which receives four pieces of information that uniquely define the track. The input to MLU K is the polarity and momentum of the track from MLU J as well as two angles of which at least one must be the original unrotated coordinate. It receives this information in a 21-bit input word configured as follows:

where ξ is the polarity, p is the momentum, θ_2 is the WC2 angular data obtained directly from data stack D and θ'_1 is the rotated and filtered ($-32^\circ \leq \theta'_1 < 32^\circ$) WC1 angular data from MLU I. Note that only the eight most significant bits of θ_2 and the six most significant bits of θ'_1 are used, thus truncating them to units of 2° and 1° respectively. The scattering angle with respect to the θ_2 direction is calculated from the momentum, polarity and θ'_1 and this is converted to the absolute scattering angle by adding θ_2 . The final 2° angular resolution in the scattering angle is not such a serious drawback given the range of angles over which the cut applies. This stage would not be possible at all without the 21-bit MLU.

6. The momentum sum cut

For $(\pi, 2\pi)$ experiments an alternative second stage is used. The main concern for these experiments is separating the $(\pi, 2\pi)$ events from the much more numerous π -p elastic scattering events. The single track finding stage is not sufficient for this purpose as there is a significant overlap in the momentum distributions of the outgoing charged particles from the elastic scattering and $(\pi, 2\pi)$ reactions. This is especially so

for reactions initiated by a positively charged pion. The second level trigger cannot do any particle identification so if either the outgoing π^+ or p from elastic scattering has a momentum in the range expected for charged particles from $(\pi, 2\pi)$ then the track finding stage would issue an accept.

The total kinetic energy of the two outgoing charged particles provides a kinematic separation between the two types of reactions as the extra pion rest mass and neutron kinetic energy are not accounted for in the $\pi^+p \rightarrow \pi^+\pi^+n$ reaction. Thus the sum of the squares of the momenta of the two charged particles can be used to discriminate between events from that reaction and those from elastic scattering. Monte Carlo generated distributions of the sum of the squares of the momenta of the two final state charged particles are shown in fig. 6 for elastic scattering and the $(\pi, 2\pi)$ reactions at an incident pion energy of 280 MeV. Note that the $\pi^+p \rightarrow \pi^+\pi^0p$ reaction is also of significant interest and the inability of the second level trigger to do particle identification limits the usefulness of a kinetic energy cut. Nevertheless the momentum sum cut is still crucial to the $(\pi, 2\pi)$ experimental program in limiting the number of elastic scattering events recorded.

Unlike the previous stage, this stage requires more than one good track to be found by the primary stage. The momentum and polarity of the first track found must be stored and then summed with the momentum of the next track found. The circuit that achieves this is shown in fig. 7. The momentum and polarity result of the primary stage are first stored in the data register. The inverted read ready (RR) output of the data register is used as a NEXT pulse to initiate a search for a second acceptable track. The primary stage will continue from where it left off in the list of WC1, WC2 and WC3 angle combinations. The RR of the data register is also used to set latch L3 that disables further input to the data register and enables the input to MLU L. If a second good track is found, the momentum and polarity appear on the upper seven bits of the input to MLU L. The results of the first track are also present on the lower seven bits having been held there by the data register. The good track pulse strobes MLU L which is preloaded with the result of the momentum sum cut given all possible input combinations of the fourteen bits. If the sum of the squares of the momenta is below the upper limit then a final second level trigger YES pulse is produced. A negative result is fed back to the primary stage as a NEXT pulse to force a search for a third acceptable track. At the same time latch L4 is set which disables further input to MLU L. This latch also opens gate G14 which passes a third good track pulse to the second level YES output. Three track events are sufficiently rare and of enough potential interest that they are always passed by the second level trigger.

7. Muon rejection

There is another section of the second level trigger that is not dependent on the track finding stage and in fact can disable the processing of the track finding stage. This part is responsible for ensuring that the incoming beam particle has the correct incoming trajectory by requiring a hit in each of WC1 and WC2 in the appropriate region. It removes a large fraction of events initiated by a muon from in-flight pion decay that does not follow the incoming beam trajectory. The trajectory of an outgoing muon resembles that of a forward scattered pion and the trajectory of an incoming muon resembles that of a back scattered pion of opposite polarity to that of the beam.

Thus the pattern of hits often passes the track finding stage and, depending on the configuration of the other stages, may otherwise cause many of these events to be recorded.

The implementation of this stage is shown in fig. 8. The ECL port output of the WC1 and WC2 PCOS controller is fed to MLU M and then daisy-chained to MLU B of the track finding section. The width bit is also daisy-chained so that data words representing the width of a cluster are ignored. MLU M is programmed to set the lowest bit of the output whenever an input word corresponds to a WC1 hit in the region of the incoming beam and to set the second-lowest bit whenever an input word corresponds to a WC2 hit in the incoming beam region. For all other input words the output is all false. Thus latches L5 and L6 will both be set whenever there is an incoming beam particle with the correct trajectory. The AND of the outputs of these two latches goes to Latch L1 of the track finding stage. If this does not go TRUE before the ADI signal arrives then latch L1 will not be set and processing will not begin. Instead the ADI signal will pass gate G8 and become the REJECT pulse. In this way the circuit rejects events that do not have a good incoming beam track.

8. Resolution

The input to the second level trigger is only a small fraction of the total data available to CHAOS. In particular, the drift time information from WC3 and WC4 is not available. The resolution of quantities upon which the second level trigger bases its decisions is not nearly as good as that obtainable in offline event reconstruction. Thus, in order to decide how tightly to set the second level trigger limits it is important to know how accurately these quantities can be determined by the second level trigger electronics.

8.1. Momentum

A major component of the second level trigger decision is based on the momentum of a track found by the primary stage. In order to set limits it is important to know the distribution of momenta calculated by the second level trigger algorithm that would result from a mono-energetic particle beam passing through CHAOS. Fig. 9 shows the momentum of the outgoing beam track as calculated using the second level trigger algorithm for a 225 MeV/c π^- beam in a 0.5 T magnetic field. There was no target for this run and the second level trigger was not part of the event trigger so that the incoming and outgoing beam tracks were recorded. The major source in the spreading is due to the $\frac{5}{4}^\circ$ angular resolution obtainable from WC3. Note also that if a particle passes close to the midpoint of two wires and both fire then PCOS clusterises the data to achieve this resolution. If however only one of the wires registers a hit then the effective resolution becomes $\frac{5}{2}^\circ$. Monte Carlo simulations with various probabilities of the two cases were performed until the resulting momentum distribution resembled that found experimentally. This was then used to determine the FWHM of the momentum distribution as a function of particle momentum and magnetic field strength. The result for a 1.0 T field is shown in fig. 10.

8.2. Distance of closest approach

In the track finding stage a cut is made on the distance of closest approach of the track to the target centre. The simulation program used for the momentum resolution was also used to determine this quantity, d , for each track. The distribution of d for the simulated tracks was uniform out to some chosen radius. The reconstructed distance was calculated from the digitised PCOS coordinates using a realistic WC3 angular resolution as determined in the previous section.

A histogram of the simulated reconstructed distance with a target radius of 15 mm is shown in fig. 11. Also shown is the histogram of the exact distance for this case. The largest contribution to the broadening is from the limited angular resolution of WC3. From this simulation it is possible to estimate the effect of various cuts on the distance parameter. A cut on the distance of closest approach at 15 mm would result in a loss of about 8% of events that actually came from within 15 mm of the origin. Increasing the target cut to 18 mm would ensure that the fraction of events from within 15 mm of the the origin that are lost is about 1.5%. A cut 20 mm would ensure that the fraction lost is insignificant.

8.3. Momentum sum

The effect of the momentum resolution on the sum of the squares of the momenta and in particular the ability of the second level trigger to discriminate between $(\pi, 2\pi)$ reactions and πp elastic scattering was simulated in much the same way as the resolution for single momenta. However, instead of assuming a monoenergetic source, a set of pairs of momenta of the outgoing charged particles from a $(\pi, 2\pi)$ reaction was generated using a Monte Carlo program based on the three body phase space of the final state. For each pair, a random track with the momentum of the first particle was simulated. The track coordinates were then rounded off to mimic PCOS digitisation and the momentum was recalculated according to the second level trigger algorithm. The same operation was performed on the momentum of the second charged particle in the pair. The squares of these momenta were then summed according to the six bit resolution available from MLU K.

The results of the simulation for 280 MeV incident pions and a magnetic field strength of 1 T are shown in fig. 12. The results are in the form of histograms of the reconstructed momentum squared sums of the final state charged particles from πp elastic scattering and the $\pi^+ p \rightarrow \pi^+ \pi^+ n$ reaction assuming a realistic angular resolution in the data available to the second level trigger. These are to be compared with the histograms shown in fig. 6. The major effect of the rounding of PCOS coordinates is to produce a drawn-out tail on the high momentum side. This is as expected. That is, the momentum resolution is poorer for higher momenta since for straighter tracks, a small error in one of the angles has a larger effect on the reconstructed momentum. Nevertheless, the plots also demonstrate that the momentum sum section of the second level trigger still provides a good filter between elastic scattering and the $\pi^+ p \rightarrow \pi^+ \pi^+ n$ reaction. In particular, approximately 1% of the $\pi^+ p \rightarrow \pi^+ \pi^+ n$ events have a value for the reconstructed momentum squared sum that is above $0.07 (\text{GeV}/c)^2$ and less than 0.1% of the elastic events have a value below this limit. However, since the first level trigger rate for $\pi^+ p$ elastic scattering is approximately 3500 times higher than that for $\pi^+ p \rightarrow \pi^+ \pi^+ n$, the fraction of $(\pi, 2\pi)$ events passed by this cut is about 30%. The

situation is better for the reaction initiated by a π^- , as the first level trigger rate of $\pi^- p$ elastic scattering is only about seventy times greater than that for $\pi^- p \rightarrow \pi^+ \pi^- n$ leading to about 95% of the events that pass the $0.07 (\text{GeV}/c)^2$ cut being $(\pi, 2\pi)$ events.

9. Trigger operation

The first step in using the second level trigger is to decide the configuration that will be used. The choice of which, if any, secondary stage to use is made by connecting the **Good Track** output of the primary stage to the appropriate input of the chosen secondary stage. If desired, both secondary stages can be used by connecting the output of the momentum versus scattering angle stage to the input of the momentum sum stage. The output of the final stage is then used as the second level trigger **Accept**. These connections are easily achieved through the use of two NIM cables between various channels of an ECL-NIM-ECL converter that acts like a simple patch panel. The Muon Rejection stage can be disabled through software by defining the incoming beam region in WC1 and WC2 to be the whole angular range.

The next step is to decide on the limits that are to be set on the quantities that are estimated by the second level trigger. In the unrealistic case of perfect resolution, the limits are those determined from kinematics alone (see for example fig. 4). In the realistic case the resolution must be considered as described in section 8. As a further aid to optimising the limits at the beginning of an experiment, data are collected without the requirement of a second level accept in the master trigger. The operation of the second level trigger is simulated by the CHAOS online analysis software. Various histograms and scatter plots of the quantities estimated by the second level trigger algorithm can be observed and the effects of various cuts investigated. The chosen limits together with the CHAOS field, the beam momentum and the beam polarity form the input to a program which calculates what the contents of each MLU in the second level trigger should be. The results are stored in files which can be easily downloaded into the MLU's through a versatile menu-driven program [5] that allows the user to interact easily with the trigger modules. This program is also used to set the delays and ALU operations. Note that MLU's A, B, H and I deal only with raw angular data in the form of PCOS addresses and so their contents need only be calculated once.

9.1. Diagnostics

The performance of the second level trigger is continually monitored during data acquisition. In the initial testing stages, the decision (accept or reject) is fed directly to the data acquisition computer. This result is checked for each event by the online analysis software which simulates the action of the second level trigger using the raw PCOS addresses in conjunction with the parameters with which the second level trigger was programmed. This same check is continued when the second level trigger is used to reject unwanted events. To ensure that the second level trigger is not rejecting interesting events, a small random sample of the rejected events are actually recorded and the reject decision made by the second level trigger is checked by the online analysis software.

The time for the second level trigger to reach a decision is also calculated for

each event recorded. This is achieved in the simulation software by summing the times taken for each step in the second level trigger algorithm. With sufficient data and hits in the incoming beam region, the time taken to reach a decision depends on the number of times the loop is executed and on where in the loop the NEXT pulse is generated. The track finding stage takes about 220 ns for each combination of hits, though it can generate a NEXT pulse in about 170 ns when the track failure occurs at MLU I or MLU J. If the momentum versus scattering angle cut is used as the secondary stage, then a further 80 ns will be required so the shortest time that the second level trigger can reach a YES decision after the ADI signal is about 300 ns. With the momentum sum stage, at least two tracks must be found. The time for a NEXT pulse to propagate back to the data stacks is about 70 ns and with the processing time of the extra stage, the minimum time for a YES decision is about 630 ns.

The time taken to reach a second level NO decision is roughly proportional to the number of combinations that must be tried. For example, if there are two hits in each of WC1, WC2 and WC3 then the trigger tries all eight combinations until a successful combination is found. A second level NO will be generated only when all eight have been tried and failed. The time for each loop depends on where in the loop the failure occurs and also on which secondary stage is being used but, as a guideline, each loop takes an average of about 300 ns including the time for the NEXT pulse to propagate back to the data stacks. Most reject decisions are made in under 6 μ s and the average time is between 2 μ s and 4 μ s. This depends on the average number of hits in each chamber and thus on the specific experimental configuration such as the target, beam momentum and beam polarity. A histogram of the time for a second level reject decision is shown in fig. 13. These times were calculated using data that were recorded without the requirement of a second level accept in the event trigger at a π^+ beam energy of 280 MeV on a CH_2 target in a 1 T field. In this case, a second level accept corresponded to the kinematic conditions for a $\pi^+p \rightarrow \pi^+\pi^+n$ reaction and so included the momentum sum stage but not the momentum versus scattering angle stage.

10. Conclusions

The second level trigger is vital to the success of the CHAOS project. It allows fast rejection of events based on track existence, momentum, interaction region, polarity, momentum as a function of scattering angle and the sum of momenta from two detected tracks. In addition, it can reject events that do not have a good incoming beam trajectory. It has been implemented using LeCroy ECLine fast trigger modules augmented by more powerful 21-bit MLU's of our own design. The entire trigger system is contained in a single CAMAC crate and bases its decisions on 1584 channels of ECL input from the PCOS III system. Its flexibility ensures that minimal effort is required in order to use it for a range of experiments with different rejection criteria. The trigger parameters can be changed easily by reloading the memory lookup units.

The limitations on the use of the second level trigger stem from the incomplete information upon which its decisions are based. In particular, the resolution with which the momentum of a track can be determined restricts the event rejection power somewhat, though well-chosen experimental conditions enable a significant gain from the second level trigger.

This work has demonstrated the power of the trigger modules. In effect, a hard-

wired computer has been constructed that determines the parameters of a circle through three given points in less than half a microsecond. It makes decisions based on these parameters and loops over all combinations of the input. The technique used to construct the CHAOS second level trigger could be used for other applications although, given the unique nature of large detectors, each project would require significant effort.

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Figure captions

1. The layout of the CHAOS facility and the tracks of an example event.
2. A schematic representation of the reduction algorithm.
3. The full schematic circuit diagram of the primary stage of the second level trigger.
4. The pion momentum versus scattering angle after elastic scattering off hydrogen, helium and carbon for an incident pion energy of 100 MeV. The error bars indicate a $\pm 5\%$ spread in the momentum.
5. The extra circuitry for the momentum versus scattering angle cut.

6. Monte Carlo-generated distributions of the sum of the squares of the momenta of the two final state charged particles in the $\pi^+p \rightarrow \pi^+p$ and $\pi^+p \rightarrow \pi^+\pi^+n$ reactions for incident pions of 280 MeV.
7. The schematic circuit diagram of the momentum sum cut.
8. The extra circuitry to disable trigger processing when the event does not contain hits in WC1 and WC2 in the incident beam region.
9. The momentum of the outgoing beam track as calculated using the second level trigger algorithm for a 225 MeV/c π^- beam in a 0.5 T magnetic field.
10. The FWHM of the second level trigger momentum distribution as a function of particle momentum.
11. Histogram of the reconstructed distance of closest approach to the centre of a target as simulated using a target radius of 15 mm, a magnetic field strength of 1 T and a momentum of 225 MeV/c. Also shown is the histogram of the exact distance for this case.
12. The sum of the squares of the momenta of the two charged particles in the final state of the reactions $\pi^+p \rightarrow \pi^+p$, and $\pi^+p \rightarrow \pi^+\pi^+n$ as simulated with the second level trigger algorithm for incident pions of 280 MeV and a magnetic field strength of 1 T.
13. The time for a reject decision from the second level trigger configured to accept $\pi^+p \rightarrow \pi^+\pi^+n$ events in a CH_2 target with a beam energy of 280 MeV and a magnetic field strength of 1 T.

Fig. 1

Fig. 2

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Fig. 11

Fig. 12

Fig. 13