The Pretrigger System of the OPAL Experiment at LEP

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Abstract

A pretrigger system is described for running the OPAL detector at the LEP e^+e^- collider with more bunches than originally foreseen. A large number of low threshold pretrigger signals are formed by several independent components of the detector, and combined by a custom-built VME-based central pretrigger logic. Flexibility, high efficiency and high redundancy in all physics channels are all achieved with low additional deadtime, without any compromise to the trigger performance.

(Submitted to Nucl. Instr. and Meth.)

1 Introduction

The OPAL detector [1] has been in operation at the Large Electron-Positron collider (LEP) at CERN since the first collisions in 1989. Up to the beginning of 1992 LEP has run with four bunches of electrons and four bunches of positrons (“4+4”) colliding at centre-of-mass energies around the Z^0 mass. During this time 22 pb^{-1} of physics data were recorded (including 520000 $Z^0 \rightarrow q\bar{q}$ decays) using a highly efficient VME-based data collection system [2]. A hardware based trigger decision [3] is formed using a combination of signals from several components of the detector; from a bunch crossing rate of 45 kHz, the trigger system reduces the event rate to 2–3 Hz at a typical luminosity of $0.5 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$. The data are subsequently processed by a software “filter” [4] which uses a partial event reconstruction and some preliminary event classification to reduce the event rate by a further $\sim 30\%$. The filter also performs data compression before the data are stored on optical disks, in preparation for further processing.

The original trigger system was designed as a single stage trigger, because the time between a bunch crossing and the decision being made plus the time required by detector components to clear their electronics (“reset time”) amounts to $\sim 20 \mu\text{s}$, which is less than the interbunch time of $22 \mu\text{s}$ in 4+4 bunch mode. From the start of data-taking in 1992, the detector has run with a two-stage trigger system suitable for operation with more than 4+4 bunches, as shown in Fig. 1. A new first-stage (“pretrigger”) system has been incorporated with minimal disturbance to the original trigger system. With 8+8 bunches in LEP (and potentially even more bunches), the pretrigger performs a deadtime-free first level decision without compromising trigger efficiency or acceptance, reducing the 90 kHz bunch crossing rate down to a rate of positive pretriggers of 1–2 kHz. The original trigger system has remained essentially unchanged and is used as a second level trigger.

The detector is shown in Fig. 2 and comprises several “subdetectors”. The tracking of charged particles is performed within a 0.435 Tesla solenoidal magnetic field by a silicon-based microvertex detector and three drift chambers: a vertex-chamber, a large volume jet chamber, and chambers used to measure the z -coordinates¹ of tracks as they leave the jet chamber. A time-of-flight hodoscope covers the barrel region around the outside surface of the magnet coil. The electromagnetic calorimeter divides into a barrel region and two end-caps, and comprises 9440 lead-glass blocks in the barrel region and 1132 in each end-cap. Presampling devices are placed immediately in front of the lead-glass blocks. The magnet return yoke is instrumented as a hadron calorimeter, and is surrounded by muon chambers divided into a barrel and two end-caps. A calorimeter-based forward detector is used to measure luminosity.

1.1 The Original Trigger System

Central to the original trigger design [3] was the high redundancy inherent in using a large number of trigger conditions, many based on independent subdetector components. Of the sixteen subdetectors, nine (the vertex chamber and the jet chamber which together comprise the Track Trigger [5], the time-of-flight hodoscope, the barrel and end-cap electromagnetic calorimeters, the muon barrel and end-cap chambers, the hadron calorimeter, and the forward calorimeters) generate prompt digital signals available for triggering. The trigger signals are combined by a central trigger logic, which processes the signals and forms the overall trigger decision. Trigger signals divide into two complementary categories. Subdetectors provide “direct” signals such as track multiplicities or energy sums. In addition, most subdetectors contribute low threshold signals corresponding to 6×24 overlapping bins in θ and ϕ ,

¹The coordinate system has positive z along the outgoing e^- direction, with θ and ϕ denoting polar and azimuthal angles. The origin is taken as the nominal interaction point.

respectively. The θ - ϕ signals from each subdetector can be considered as forming one of several layers of a matrix in θ - ϕ space. The trigger decision is formed from a programmable combination of trigger conditions derived from the direct signals and correlations within the θ - ϕ matrix. The simplicity and flexibility of the trigger design, coupled with high redundancy of trigger signals in all physics channels, enabled the detector to trigger with high efficiency at low rate, while luminosity, backgrounds and detector noise varied.

1.2 Pretrigger Design Criteria

The principal requirements for the pretrigger system were for an acceptance that matches and an efficiency that improves on that of the trigger in all physics channels. The overall rate must be kept low, since a positive pretrigger decision preceding a negative trigger decision incurs deadtime due to unconsidered beam interactions². This called for low thresholds and a high redundancy of pretriggers in both the barrel and end-cap regions of the detector, combined with flexibility (programmability) for an effective control of the overall rate. The pretriggering philosophy adopted is conceptually similar to that of the trigger. It uses a large number of pretrigger signals, generated by independent subdetector components, that are combined by a fast programmable central pretrigger logic processor.

The design goal for the pretrigger scheme was for full efficiency for single particles. Although a single pretrigger signal from each subdetector would be sufficient for this purpose, bad background conditions could introduce an unacceptable overall pretrigger rate. Most subdetectors therefore contribute signals that correspond geometrically to segmentation in ϕ . Requiring coincidences in ϕ between subdetectors can reduce the rate of pretriggers arising from background synchrotron radiation or noise, whilst retaining full efficiency for single particles. Should the background conditions become sufficiently severe to require ≥ 2 ϕ segments or back-to-back ϕ segments either within or between subdetectors, full efficiency for fermion pairs is still retained.

In common with trigger signals, pretrigger signals divide into two complementary categories. Subdetectors may provide direct signals, such as energy sums above threshold from the calorimeters. In addition, most subdetectors contribute 12 low threshold signals which each typically correspond to 60° segments in ϕ with $\sim 30^\circ$ overlap with the adjacent segments (see Table 1). Eight sets of these low threshold signals are generated: by the vertex chamber; the jet chamber; the time-of-flight hodoscope; the electromagnetic barrel calorimeter; both electromagnetic end-cap calorimeters; and both muon end-cap chambers. The acceptance in θ matches that of the trigger θ - ϕ signals, covering $|\cos \theta| < 0.98$, and there is full coverage in ϕ . A direct signal from the forward detector completes the forward coverage. The hadron calorimeters do not contribute, and the muon barrel chambers are excluded because the drift-time is too long. Enhanced redundancy is achieved in both the barrel and end-cap regions by the separate pretrigger contributions from the vertex chamber and the jet chamber, and by setting the thresholds of the electromagnetic calorimeter pretrigger signals sufficiently low to be sensitive to minimum-ionising particles.

Pretrigger ϕ signals received by the central pretrigger logic are shown schematically in Fig. 3. The low threshold signals can be considered as forming a matrix of 8 subdetectors, or layers, in θ - ϕ space, with several layers of the matrix fully or partially sensitive to each type of particle. Multiplicity counting and spatial correlations both within and between layers, together with direct signals, provide a large number of independently formed pretrigger conditions in both the barrel and end-cap regions which can be used to form the overall decision.

²For 8+8 bunches in LEP, every 1 kHz in pretrigger rate incurs a deadtime of $\sim 1\%$.

2 Implementation of the Pretrigger

The implementation of the pretrigger scheme within the trigger system is shown schematically in Fig. 4. A bunch crossing synchronisation signal initiates the generation by subdetectors of pretrigger and trigger signals, which are then strobed several microseconds after the bunch crossing into the Central Pretrigger Logic ("CPL") and Central Trigger Logic ("CTL"), respectively. Both the CPL and CTL process the signals and form their decision in less than 200 ns. Before the next bunch crossing, the pretrigger decision is received by the Global Trigger Unit ("GTU"), which resides in the CTL. If the pretrigger decision is positive, processing of trigger signals proceeds beyond a second bunch crossing, and thus incurs deadtime.

The GTU controls synchronisation within the CTL and also broadcasts trigger information via a special trigger bus to each of the Local Trigger Units ("LTUs") located in subdetector readout crates. If either the pretrigger or trigger decision is negative, subdetectors receive a "RESET" signal. Subdetector front-end electronics are then cleared in preparation for the next bunch crossing. If the trigger decision is positive, a "TRIGGER" signal is broadcast. The LTUs then generate local VME interrupts which initiate readout of the subdetectors, and exert a "BUSY" signal on the trigger bus until their readout is complete. Further TRIGGER and RESET signals are disabled until all subdetectors have removed the BUSY signal from the trigger bus.

The implementation of the pretrigger system and timing considerations are described in the following sections. The GTU is the only component of the original trigger system which required modification. All subdetectors needed minor modifications to meet new timing constraints, and subdetectors contributing pretrigger signals required upgrades of varying degrees. The CPL is a new custom-built VME-based logic, which forms the overall pretrigger decision and handles the communication with the original trigger system.

2.1 Subdetector Synchronisation

Table 2 summarises the timing of the detector for running with 4+4 bunches in LEP (as was the case up to the middle of 1992) and for running with 8+8 bunches. The sum of the pretrigger decision time and the subdetector reset time must be less than the bunch crossing time interval, otherwise unacceptable deadtime is incurred due to unconsidered bunch crossings. In order to maximise the available pretrigger decision time, the reset time was reduced by $2\mu\text{s}$ at the start of 1992. This change in the reset time allows pretrigger signals to be generated by subdetectors and received by the CPL up to $5.3\mu\text{s}$ after an interaction. The timing of subdetector trigger signals remains unchanged and independent of the number of bunches in LEP, being received by the CTL up to $14.5\mu\text{s}$ after an interaction.

The timing diagram is shown in Fig. 5. The bunch crossing synchronisation signal is used to gate the front-end electronics of the subdetectors only if it is preceded by a RESET signal, otherwise it is ignored. The transition between running with 4+4 and 8+8 bunches therefore only requires changes centrally within the CTL, and subdetector readout and synchronisation are independent of the number of bunches in LEP.

2.2 Subdetector Pretrigger Signals

Upgrades to the trigger electronics of the muon end-cap chambers, the time-of-flight hodoscope and the forward calorimeter were relatively straightforward, since their trigger signals are formed early

enough to be used as pretriggers. For the muon end-caps and the time-of-flight, the trigger signals simply needed reformatting to conform to the segmentation and overlap required of the pretrigger ϕ signals. For the time-of-flight, a dedicated VME module [6] is used. In addition to generating the pretrigger signals, the module also generates the trigger signal inputs to the CTL; it replaces several crates of NIM logic and allows more selective triggering than was previously possible. For the forward calorimeter, direct trigger signals from each side of the detector are ORed and sent as a single direct pretrigger signal.

The other pretriggering subdetectors required more substantial upgrades in order to generate pretrigger signals. The upgrades are described in detail below.

Vertex Chamber

Pretrigger signals from the vertex chamber are derived from the number of wires with hits within each of its 36 ϕ sectors. Four different thresholds (4, 6, 8 or 10 out of 12 wires) can be used, selectable by software on a sector-by-sector basis. This option was implemented because background conditions (and hence the typical number of wires hit in background events) can change in both time and ϕ , and it can also allow for missing wires. During 1992 the threshold was set at four wires. The 36 decisions are combined into 12 to conform to the pretrigger ϕ segmentation by a custom-built VME module. Two schemes are allowed, differing in their degree of overlap and matching with other pretrigger elements. The scheme currently in use combines groups of four adjacent sectors into a single decision, with an overlap between the first and last sectors of each group of four (see Table 1). The second scheme groups six adjacent sectors and has overlap between the first three and the last three sectors in each group (i.e. there is 100% overlap).

Jet Chamber

Pretrigger signals from the jet chamber are derived from the number of wires with hits within each of its 24 ϕ sectors. This information is obtained by the track trigger electronics [5] which use three groups of 12 adjacent wires out of the 159 wires in each sector. The inner group covers $|\cos \theta| < 0.97$, the middle group $|\cos \theta| < 0.93$, and the outer group $|\cos \theta| < 0.82$. The pretrigger uses only the inner and optionally the middle group; the larger drift space of the outer group may cause its hit signals to arrive too late to contribute to the pretrigger decision. From each group, signals from corresponding wires in neighbouring sectors are ORed to account for tracks crossing sector boundaries. The number of wires hit in each sector are then summed and compared to an adjustable threshold which is typically set to 8 (out of 12). A positive decision therefore indicates a track in a $30^\circ \phi$ segment. Although not used in 1992, a coincidence requiring a track in both the inner and the middle ring of the same $30^\circ \phi$ segment may be activated to reduce background. Three adjacent overlapped $30^\circ \phi$ segments are ORed to form the 12 overlapping $60^\circ \phi$ signals sent to the CPL.

Electromagnetic Calorimeters

The original analogue summing trigger electronics of the lead glass electromagnetic calorimeter were not fast enough to be used in the pretrigger. In addition, the aim was to make even the electromagnetic pretrigger sensitive to single minimum-ionising tracks, which deposit on average ~ 500 MeV in the calorimeter. The rates of many of the calorimeter's original trigger signals were known to be dominated by low-level noise summed in the analogue summing circuits, and if any trigger threshold had been lowered sufficiently to provide good efficiency for single minimum-ionising tracks, the rate of any such signal would have precluded its use as a pretrigger. Therefore a new combined trigger and pretrigger system has been implemented [7], based on an early digitisation via flash-ADCs, programmable noise-suppression thresholds, and digital summation.

Analogue linear sums over 12 adjacent lead glass blocks were already provided by the charge-integrating readout ADCs [8]. These sums are used as inputs to new VME modules ("DL513"), each containing eight channels of 8-bit flash-ADCs, digital comparators and summing circuits. After

digitisation, those energies exceeding an individually programmable noise-suppression threshold are summed digitally to form energy sums over 48 and then 96 adjacent lead glass blocks. The sums over 48 blocks are available as 8-bit digital information from the DL513, along with the logical ORs of the outputs of the noise-suppression comparators, and the results of comparing each of the 96-block sums with an individually programmable threshold. In the barrel region fast pretrigger signals are formed directly from the DL513 outputs, while in the end-cap region there is one further stage of summing in a custom-built digital summing module.

The 12 barrel pretrigger ϕ signals are formed from the logical OR of those outputs of the noise-suppression comparators contributing to each pretrigger ϕ sector, as given in Table 1. Energy deposits from a single incident particle may sometimes be split over more than one lowest-level 12-block sum, causing the effective pretrigger threshold to rise. However, this effect is diminished by setting the nominal pretrigger threshold very low, a factor 3–4 smaller than the mean energy deposited by a minimum-ionising particle. High rates may be introduced by the low thresholds, possibly excluding the use of the ϕ signals as a single-particle pretrigger; therefore a higher threshold direct signal (“EBPHI”) is also generated from the logical OR of all 100 barrel 96-block results. For 1992, the pretrigger ϕ signal (and noise-suppression) threshold was nominally 150 MeV, and the nominal EBPHI threshold 320 MeV. The two corresponding measured efficiency curves are shown in Fig. 6. Trigger signals from the barrel calorimeter continue to be generated using the original analogue summing modules, after converting the sums over 48 lead glass blocks from digital back to analogue.

In each end-cap, a custom-built digital summing module forms both the pretrigger and trigger signals. The 8-bit DL513 sums correspond to 15° ϕ segments, and they are used to generate digital sums over the 96 lead glass blocks of each of the 24 30° ϕ sectors of the trigger. The 12 pretrigger ϕ signals are formed from the logical OR of the discriminated 30° sums. For 1992, the DL513 noise-suppression threshold was nominally 190 MeV. The measured efficiency curve for the pretrigger ϕ signals is also shown in Fig. 6. For triggering purposes, each 30° sum is compared with a second (higher) programmable threshold, and all 24 outputs logically ORed to generate the localised energy trigger signal originally formed via analogue electronics [3]. The 30° sums are also converted from digital back to analogue, and are sent to the barrel analogue summing modules, to contribute to the θ - ϕ trigger signals. The original trigger signals indicating total energy in an end-cap above threshold are now generated digitally.

The concept of a noise-suppression threshold followed by digital summing has allowed a substantial (30%–50%) reduction of all the thresholds of the electromagnetic calorimeter trigger signals.

2.3 The Central Pretrigger Logic

The CPL is housed in a modified VME crate, with a dedicated internal bus on the J2 backplane between slots 10 and 20. The crate contains 10 purpose-built pretrigger modules for the processing and monitoring of pretrigger signals, and up to 9 standard VME boards. It is memory-mapped to the CTL via VICbus [9], and controlled by two single-board computers based on the 68020 and 68040 microprocessors³, which reside in the CTL. The modules of the CPL are listed below.

- The pretrigger single input module (“PSIM”) receives up to 24 direct pretrigger signals in NIM from the subdetectors. The signals are accepted within a gate $5.3\mu\text{s}$ wide following a bunch crossing. The PSIM shares many common features with an equivalent module in the CTL, and will not be discussed further.

³The 68020 processor performs the readout, and the 68040 processor performs all other tasks including control and monitoring.

- There are four dual ϕ modules (“DPHIs”) in the CPL. Each DPHI module receives two sets of 12 differential ϕ signals from a pair of subdetectors, and performs ϕ matrix correlations.
- The pretrigger pattern match module (“PPAM”) combines the PSIM signals and the ϕ -matrix correlations to form the final pretrigger decision.
- The pretrigger synchronisation module (“PSYN”) controls the synchronisation of the CPL, and transmits the overall pretrigger decision to the CTL.
- Some additional modules are dedicated to monitoring.

The Dual ϕ Modules

Each DPHI module determines hit multiplicities and correlations in the ϕ segments within a single subdetector and between the pair of subdetectors. The four DPHI modules also determine correlations in the ϕ segments between the vertex and jet chambers and all other subdetectors. The DPHI modules are physically identical but their function is defined by jumpers on the VME board. One module receives signals from the vertex and jet chambers, one the electromagnetic calorimeter barrel and time-of-flight hodoscope, one the two end-caps of the electromagnetic calorimeter, and one the two end-caps of the muon chambers. Each of the eight sets of signals are latched independently by strobes generated between $\sim 1 \mu\text{s}$ and $5.3 \mu\text{s}$ after the bunch crossing, depending on the arrival time of subdetector signals. For each set of 12 ϕ signals, the DPHI module performs multiplicity counting (≥ 1 hit if any segment is set and ≥ 2 hits if two or more non-adjacent segments are set) and looks for back-to-back (opposite ϕ) correlations. Between each pair of subdetectors, the DPHI module looks for correlations in same- ϕ and opposite- ϕ segments. Same- ϕ and opposite- ϕ correlations between each subdetector and the vertex and jet chambers are determined using a dedicated bus which interconnects all the DPHI modules across the front panel. A total of 40 correlations are determined within the ϕ -matrix (see Table 3). The 40-bit result is stored in registers accessible through VME, and transmitted via the internal bus to the PPAM module. The 40 results are also available in NIM for use as possible direct trigger signals.

The Pretrigger Pattern Match Module

The logic of the PPAM is shown schematically in Fig. 7. It receives the 24 PSIM outputs and 40 ϕ -matrix outputs via the internal bus and stores them in a register. The signals are arranged in four groups of 16, each of which acts as the address to one of four first-level static RAMs used as a look-up table. The four outputs, one from each of the four first-level RAMs, are grouped together and used as the address to a second-level look-up RAM. Both levels of RAMs are preloaded with appropriate data corresponding to the required logical combination of PSIM and ϕ -matrix conditions. Splitting the 64 inputs to the PPAM among the four first-level RAMs imposes logical constraints on the possible number of pretrigger conditions, therefore both levels of RAMs are effectively repeated in eight “layers”: there are eight data bits at each address of the first-level RAMs, and eight second-level RAMs. The look-up RAMs can therefore be preloaded with eight independent configurations, and the overall pretrigger decision is the logical OR of all eight of them. A positive result from any of the eight layers can be optionally prescaled by factors of 2, 4, 8 or 16.

The logical OR of a programmable subset of the eight layer results is available in NIM. This feature is useful for flagging special pretrigger conditions independent of the overall pretrigger decision, e.g. to use a combination of pretrigger conditions as a direct trigger input to the CTL.

The Pretrigger Synchronisation Module

The PSYN module receives one of four gates (selectable by software, but usually the bunch crossing synchronisation signal) in NIM and generates the strobes within the CPL. If the PPAM decision is negative, the PSYN generates a RESET signal at fixed time after the gate. If the PPAM decision is positive, the PSYN waits for a signal from the CTL which flags either a negative trigger decision or the completion of the readout of all subdetectors following a positive trigger decision. The PSYN

then generates a RESET signal at the same time after the gate as in the case when the RESET follows a negative PPAM decision; this is possible because the time between a trigger decision and the following bunch crossing is longer than the time between a pretrigger decision and the following bunch crossing. RESET signals generated by the PSYN are received by the GTU and broadcast immediately to subdetectors via the trigger bus. The timing of all RESET signals seen by subdetectors is therefore determined by the PSYN regardless of the condition that gave rise to the RESET. The RESET signal is also available directly from the PSYN in NIM, with jitter $\leq 1\text{ns}$, for those subdetectors which require a faster or higher-precision RESET than is available on the trigger bus, since the trigger bus has a large signal propagation delay and the GTU introduces a $\sim 60\text{ns}$ jitter.

A forced pretrigger decision is useful for testing and for pedestal runs in which an event is to be triggered without any bias from collisions or background in the LEP machine. Control registers are therefore implemented within the PSYN which optionally allow the PPAM output to be ignored and either a negative or positive pretrigger decision to be generated.

Control and Monitoring

Control, monitoring and readout of the pretrigger are merged with that of the trigger using the two microprocessors within the CTL. The CTL itself is connected to the VME tree-structured readout system, as part of the data acquisition [2]. The central run control supplies the parameters to configure and control the pretrigger and trigger via commands sent over the Ethernet local area network.

Before data-taking commences, the PPAM look-up RAMs are loaded according to the required combination of pretrigger conditions. Pretrigger conditions are defined in a file which identifies the pretrigger signals in use in addition to the RAM configurations. The pretrigger definition file is stored in a database [10] and is subsequently available offline during event analysis. Following a positive trigger decision, the PSIM and DPHI inputs, the DPHI outputs and the eight PPAM layer results and their prescale counts are read out, formatted and included in the trigger raw data. The data are also stored in arrays for online histogramming and monitoring. Highly effective monitoring of the CPL hardware on an event-by-event basis is performed by a simulation of the DPHI outputs and the PPAM decision, from the known PSIM and DPHI inputs.

The CPL contains three modules dedicated to monitoring pretrigger conditions. One contains 24, and another 40, 32-bit scalars which count the direct signals and ϕ -matrix outputs, respectively. The relative rates and individual rate histories of the PSIM inputs and ϕ -matrix outputs are histogrammed. The third module contains a FIFO buffer which stores the 24 PSIM and 40 ϕ -matrix output bit patterns if the pretrigger decision is positive. The FIFO stores up to 2048 such bit patterns, which are read out regularly and used for an online analysis of the contributions from individual pretrigger conditions, independent of the trigger decision. The pretrigger bit patterns for events with a positive pretrigger decision and for events with a positive trigger decision are histogrammed. In total, several hundred online histograms are generated; they are accessible by a Macintosh II computer linked to the CTL [11], and also viewable from any remote workstation. A subset of the histograms are permanently displayed [12] in the control room. Automatic monitoring of histograms is performed by one of the microprocessors, and both visual and audible warnings are generated in the control room if problems are detected. For future reference, at the end of each run a breakdown of the contribution of individual pretrigger conditions to the overall rate are stored in a database [13] and online histograms are stored.

3 Performance of the Pretrigger System

The pretrigger system was incorporated into the OPAL trigger system at the start of 1992, and was used passively during the first half of 1992 while LEP was operating with 4+4 bunches. During this

time, the bunch crossing signal was used as the pretrigger while the subdetector pretrigger signals were fully commissioned. The switch to running with 8+8 bunches in the second half of 1992 simply required a reconfiguration of the PPAM RAMs according to the required pretrigger definition.

The available pretrigger signals are listed in Tables 3 and 4, together with their rates during a typical fill in 1992 with 8+8 bunches. The pretrigger conditions which were selected within the PPAM to contribute actively to the pretrigger decision are listed in Table 5. For maximum redundancy, the final pretrigger decision should be formed by the logical OR of the single particle pretriggers ($\geq 1 \phi$ segment) from each independent subdetector component. Only the CV1 and EB1 single particle pretriggers were excluded⁴. Single-particle ϕ -matrix pretriggers from CV and EB were regained for charged tracks by requiring the coincidence between CV1 and EB1. In addition, the direct signal EBPHI generated by EB was used as a higher threshold single particle pretrigger. Single-subdetector pretriggers from CV and EB, sensitive to two or more particles, were obtained by including CV2 and EB2 in the list of active pretriggers. The maximum overall pretrigger rate was 1.0–1.5 kHz at a luminosity of $0.8 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$, which induced an additional $\sim 1.5\%$ deadtime to the experiment.

Fig. 3 illustrates the high level of redundancy available and indicates which subdetector components are fully or partially sensitive to different particles. The pretrigger efficiencies for visible Z^0 decays are listed in Table 6. The pretrigger efficiency for Z^0 decays into two neutrinos and an initial state photon, where the photon deposits more than about 1 GeV, is 100% using EBPHI, EEL1 and EER1. The overall pretrigger efficiency, within an acceptance of $|\cos \theta| < 0.97$, is 100% for single particles.

For future LEP runs, possibly with higher backgrounds, it may become necessary to change to a more restrictive set of pretrigger conditions in order to limit the overall rate. However, tighter pretrigger conditions, e.g. requiring a coincidence in ϕ between subdetectors or imposing a back-to-back requirement in ϕ , will not lead to any compromise in efficiency, given the high level of redundancy.

The pretrigger system is suitable for running with up to 18+18 bunches in LEP. However, both the pretrigger decision time and the reset time would have to be reduced, and some subdetectors would require additional upgrades.

4 Summary

A pretrigger system which enables OPAL to continue to trigger efficiently with more bunches in LEP than was originally foreseen has been commissioned with minimal disturbance to the original trigger system. Trigger performance is retained with 8+8 bunches by incorporating in the pretrigger design many of the highly successful features of the original trigger system, combining high redundancy of subdetector signals with the flexibility and simplicity of the central pretrigger logic. The pretrigger has full efficiency for single particles while maintaining a low ($\leq 1.5\%$) deadtime. More restrictive pretriggering may be implemented given higher luminosities or backgrounds without any compromise to efficiency.

⁴The rate of CV1 was too high. Although the rate of EB1 in Table 3 is acceptable, EB1 initially had a rate of ~ 3 kHz at the start of 8+8 running in 1992. The threshold was subsequently raised and the rate fell to its current value, though a change in the pretrigger definition was deemed unnecessary given the existing high level of redundancy.

Acknowledgements

That the pretrigger system could be designed, constructed and implemented within the original trigger system so smoothly and in such a short period of time is due primarily to the full and enthusiastic support of our collaborators. In particular, R.-D. Heuer of CERN and A. Wagner of DESY gave invaluable support and ideas in the early stages of the pretrigger project. The following engineers and physicists were central in the implementation of various parts of the project: A. Corre of CERN, R.G. Kellogg of the Department of Physics and Astronomy, University of Maryland, P. Rabbetts of RAL, A. Rausch and P. von Walter of Physikalisches Institut, Universität Heidelberg. The highly successful implementation of the 8+8 bunch scheme at LEP, and the smooth and efficient operation of the collider throughout the year were due to the efforts of the SL Division at CERN.

We gratefully acknowledge the financial support of the following:
European Organisation for Particle Physics (CERN),
Science and Engineering Research Council, UK,
Japanese Ministry of Education, Science and Culture (the Monbusho) and a grant under the Monbusho International Science Research Program,
Direction des Sciences de la Matière du Commissariat à l'Energie Atomique, France,
Bundesministerium für Forschung und Technologie, FRG.

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- [11] MAC 7212 Macintosh to VME 32-bit Interface, from CES, CH-1213 Petit-Lancy, Geneva.
- [12] Advanced Software Concepts, 9551, Route de Saint Laurent de Var, F-06610 Gaude, France.
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Bin	CV	CJ	TB	EB	EE	ME
1	10-50	0-60	0-54	0-54	0-60	0-60
2	40-80	30-90	36-90	36-90	30-90	30-90
3	70-110	60-120	63-117	54-126	60-120	60-120
4	100-140	90-150	90-144	90-144	90-150	90-150
5	130-170	120-180	126-180	126-180	120-180	120-180
6	160-200	150-210	153-207	144-216	150-210	150-210
7	190-230	180-240	180-234	180-234	180-240	180-240
8	220-260	210-270	216-270	216-270	210-270	210-270
9	250-290	240-300	243-297	234-306	240-300	240-300
10	280-320	270-330	270-324	270-324	270-330	270-330
11	310-350	300-360	306-360	306-360	300-360	300-360
12	340-20	330-30	333-27	324-36	330-30	330-30

Table 1: Subdetector Pretrigger Segmentation in ϕ .

All angles are in degrees. The abbreviations in the first row denote the vertex chamber (CV), the jet chamber (CJ), the time-of-flight hodoscope (TB), the electromagnetic barrel calorimeter (EB), the electromagnetic end-cap calorimeters (EE), and the muon end-cap chambers (ME). Note the ϕ -segmentation for the electromagnetic end-cap calorimeters is off-set from the quoted values by $+2^\circ$ for the left end-cap, and by -2° for the right end-cap.

Date	Number of Bunches	Interbunch Time	Pretrigger Decision Time	Trigger Decision Time	Subdetector Reset Time
<1992	4+4	22.2	N/A	14.5	6.5
1992	4+4	22.2	5.3	14.5	4.5
1992	8+8	11.1	5.3	14.5	4.5

Table 2: Timing of the OPAL experiment for different bunch numbers in LEP.

All times are in microseconds. Pretrigger Decision Time denotes the latest time after a bunch crossing that the CPL receives subdetector pretrigger signals. The subdetector reset time was reduced by $2\mu\text{s}$ in 1992 in preparation for running with an active pretrigger; the change to 8+8 bunch operation in LEP from the middle of 1992 was then invisible to subdetectors.

ϕ -Matrix Signal Description	Name	Rate (Hz)
Central Vertex chamber ≥ 1 ϕ bin	CV1	2800
Central Vertex chamber ≥ 2 non-adjacent ϕ bins	CV2	500
Central Vertex chamber ≥ 1 pair opposite ϕ bins	CVOP	220
Central Jet chamber ≥ 1 ϕ bin	CJ1	270
Central Jet chamber ≥ 2 non-adjacent ϕ bins	CJ2	160
Central Jet chamber ≥ 1 pair opposite ϕ bins	CJOP	80
Time-of-Flight ≥ 1 ϕ bin	TB1	32
Time-of-Flight ≥ 2 non-adjacent ϕ bins	TB2	2.9
Time-of-Flight ≥ 1 pair opposite ϕ bins	TBOP	1.0
EM Barrel ≥ 1 ϕ bin	EB1	300
EM Barrel ≥ 2 non-adjacent ϕ bins	EB2	2.5
EM Barrel ≥ 1 pair opposite ϕ bins	EBOP	0.9
EM End-Cap ≥ 1 ϕ bin in LEFT end-cap	EEL1	28
EM End-Cap ≥ 1 ϕ bin in RIGHT end-cap	EER1	38
EM End-Cap ≥ 1 pair opposite ϕ bins in opposite end-caps	EELRO	0.1
Muon End-Cap ≥ 1 ϕ bin in LEFT end-cap	MEL1	32
Muon End-Cap ≥ 1 ϕ bin in RIGHT end-cap	MER1	15
Muon End-Cap ≥ 1 pair opposite ϕ bins in opposite end-caps	MELRO	0.2
Same ϕ bin hits in CV and CJ	CVCJS	210
Opposite ϕ bin hits in CV and CJ	CVCJO	170
Same ϕ bin hits in TB and EB	TBEBS	1.7
Opposite ϕ bin hits in TB and EB	TBEBO	0.5
Same ϕ bin hits in TB and CV	TBCVS	22
Opposite ϕ bin hits in TB and CV	TBCVO	21
Same ϕ bin hits in EB and CV	EBCVS	4.6
Opposite ϕ bin hits in EB and CV	EBCVO	4.5
Same ϕ bin hits in EE (left OR right) and CV	EECVS	1.5
Opposite ϕ bin hits in EE (left OR right) and CV	EECVO	1.5
Same ϕ bin hits in ME (left OR right) and CV	MECVS	0.6
Opposite ϕ bin hits in ME (left OR right) and CV	MECVO	0.6
Same ϕ bin hits in TB and CJ	TBCJS	17
Opposite ϕ bin hits in TB and CJ	TBCJO	15
Same ϕ bin hits in EB and CJ	EBCJS	2.1
Opposite ϕ bin hits in EB and CJ	EBCJO	2.0
Same ϕ bin hits in EE (left OR right) and CJ	EECJS	1.2
Opposite ϕ bin hits in EE (left OR right) and CJ	EECJO	0.9
Same ϕ bin hits in ME (left OR right) and CJ	MECJS	0.2
Opposite ϕ bin hits in ME (left OR right) and CJ	MECJO	0.2

Table 3: ϕ -Matrix Output Signals

The rates in column 3 correspond to a typical 1992 fill with 8+8 bunches, average luminosity $0.5 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$, and total electron and positron currents of about 1300 μA each.

Direct Signal Description	Detector	Name	Rate (Hz)
EM Energy in barrel ≥ 320 MeV	EB	EBPHI	21
FD pretrigger OR	FD	FDPRE	14
Random Beam Crossing	CTL	BXR	4
Forced Pretrigger	Any	PRTACC	0.04
Beam Pickup Signal	CTL	BPCKUP	45 or 90 kHz

Table 4: Direct Pretrigger Signals Provided by Subdetectors

The rates given in column 4 correspond to a typical fill in 1992 with 8+8 bunches, average luminosity $0.5 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ and total electron and positron currents of about $1300 \mu\text{A}$ each. The abbreviations in column 2 denote the electromagnetic barrel calorimeter (EB) and the forward detector (FD). Special test or calibration direct trigger inputs must be duplicated and also used as direct pretrigger inputs if the event is to be accepted. BXR is used as a direct trigger input for use as a random trigger, and PRTACC was used in 1992 for calibration triggers. The BPCKUP signal was used only for running with 4+4 bunches.

Pretrigger Condition	Rate (Hz)
CJ1	270
TB1	32
EEL1	28
EER1	38
MEL1	32
MER1	15
CV2	500
EB2	2.5
CV1.AND.EB1	12
EBPHI	21
FDPRE	14
BXR	4
PRTACC	0.04
Logical OR	780

Table 5: Active Pretriggers in 1992 with 8+8 bunches in LEP.

The rates in column 2 correspond to a typical 1992 fill with 8+8 bunches, average luminosity $0.5 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$, and total electron and positron currents of about $1300 \mu\text{A}$ each. Each of the pretrigger conditions listed were logically ORed to form the final pretrigger decision.

Pretrigger Condition	Acceptance $ \cos \theta $	Efficiencies			
		$Z^0 \rightarrow q\bar{q}$	$Z^0 \rightarrow e^+e^-$	$Z^0 \rightarrow \mu^+\mu^-$	$Z^0 \rightarrow \tau^+\tau^-$
CJ1	< 0.97	100	100	100	100
TB1	< 0.82	100	100	98.4 ± 0.2	99.9 ± 0.1
EE1	$0.81-0.98$	100	100	71.4 ± 1.5	87.5 ± 1.5
ME1	$\sim 0.67-\sim 0.98$	11.6 ± 0.2	0	92.8 ± 0.1	30.5 ± 2.1
CV2	< 0.97	100	100	100	99.9 ± 0.1
EB2	< 0.82	100	100	98.4 ± 0.2	99.5 ± 0.1
EBPHI	< 0.82	100	100	97.6 ± 0.3	99.9 ± 0.1
CV1.AND.EB1	< 0.82	100	100	99.9 ± 0.1	99.9 ± 0.1

Table 6: Pretrigger Acceptances and Efficiencies for Different Physics Processes.

In the first column, EE1 denotes the logical OR of the electromagnetic calorimeter end-cap pretriggers EEL and EER, and ME1 denotes the logical OR of the muon end-cap chamber pretriggers MEL and MER. Quoted efficiencies are in %, and calculated within the quoted acceptances.

Figure Captions

Fig. 1: Overview of the two-stage OPAL Trigger System.

Fig. 2: General Layout of the OPAL Detector.

Fig. 3: Schematic of the Pretrigger ϕ -Matrix.

The vertex chamber (CV), the jet chamber (CJ), the time-of-flight hodoscope (TB), the electromagnetic barrel calorimeter (EB), the two electromagnetic calorimeter end-caps (EEL, EER) and the muon end-cap chambers (MEL, MER) each contribute a set of 12 ϕ signals to the ϕ matrix. Crosses on the horizontal lines representing different particle types passing through the detector indicate the sensitivity at the pretrigger level.

Fig. 4: Overview of Event Triggering.

Fig. 5: Subdetector Synchronisation.

A high precision bunch crossing synchronisation signal is generated 800 ns before an interaction and used by subdetectors to gate their electronics. If the pretrigger or trigger decision is negative, or if the readout is completed following a positive trigger decision, subdetectors receive a RESET signal to clear their electronics. Only the bunch crossing synchronisation signal that is directly preceded by a RESET signal is valid for gating the subdetectors, or the RESET signal itself may be used as a gate if suitably delayed. Subdetectors are thereby independent of the frequency of the bunch crossing synchronisation signal.

Fig. 6: Efficiency Curves as a Function of Deposited Energy for the Electromagnetic Calorimeter Pretrigger Signals EB1, EBPHI, and EEL(R)1.

EEL(R)1 denotes both EEL1 and EER1.

Fig. 7: Schematic of the Pretrigger Pattern Match Module.

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