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The Trigger of Beijing Spectrometer

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This article describes the functions and decision process of the trigger of Beijing Spectrometer and explains its physical considerations and compositions individually.

1. INTRODUCTION

Beijing Spectrometer (BES) is a general-purpose spectrometer installed at the first colliding point of Beijing Electron-Positron Collider (BEPC). It is used to detect and record elementary particles produced in the electron and positron collision process [1].

The designed luminosity (L) of BEPC is 1.7×10^{31} cm^{-2}s^{-1} at the energy of 2.8 GeV. L is proportional to E^2 below 2.8 GeV, and the cross section of producing lepton pair is:

$$\sigma_1(e^+e^- \to 1^+1^-) = 86.8/E^2 \mathrm{cm(nb)}$$

The event rate of $e^+e^- \to 1^+1^-$ is $n_1 = L \cdot \sigma_1 = 0.05$ s^{-1}, almost irrelevant to energy. The rate of producing hadrons is $n_h = R \cdot n_1 \approx 0.2$ s^{-1}. At J/ψ resonance peak, the event rate is much higher. Assuming that energy divergence $\sigma_E = 0.7$ MeV and detection efficiency $\varepsilon = 0.8$, according to the luminosity reached at 1.55 GeV, we calculate the event rate of J/ψ and obtain:

$$n_{J/\psi} = \int \sigma_\psi(E) dE \cdot \frac{L\varepsilon}{2\sqrt{\pi}\,\sigma_E} = 3.4 \mathrm{s}^{-1}.$$

But meanwhile a large amount of background exists. For example, the cosmic-ray background on Time-of-Flight counter (TOF) is about 1600 s^{-1}; the beam-gas background, dependent on the vacuum in the beam pipe at colliding area, is about 2×10^4 s^{-1}; the background on TOF counter

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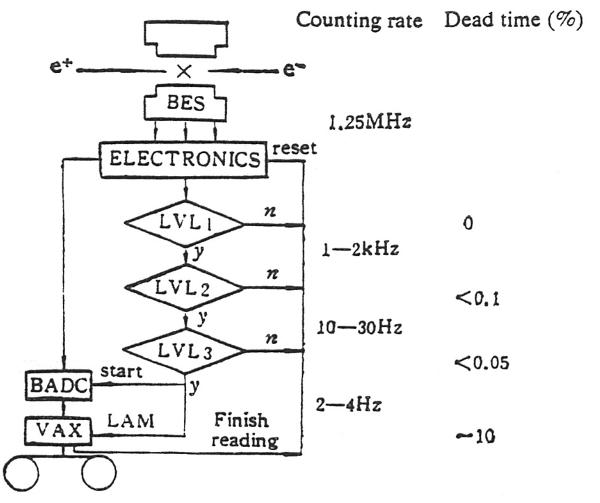

Fig. 1
The decision flow chart of the trigger of BES.

caused by synchrotron radiation may be up to about $10^5\ s^{-1}$. The read-out system of BES employs CAMAC bus and BADC. A BADC spends 20 ms to convert up to 1700 channels of stored analogy signals. This, coupled with the time used by VAX785 computer to respond to interruption, read and record, makes a total time of 40 ms. The time spent on offline analysis and track reconstruction is ten times more than that on an online computer. So it cannot record so much background. Even recording one more background event per second will make a loss of 4% of the useful luminosity.

Trigger is a fast real time event selecting and control system of Beijing Spectrometer. It is used to accelerate the selection of the signals from several thousand channels of various detectors, suppress background from $10^5\ s^{-1}$ to less than $1\ s^{-1}$, keep all good events, and minimize the dead time. The system also was designed to be flexible enough to meet the various physical demands [5,6].

All the triggers of collider spectrometers in the world are almost the same in principles. But how to realize its aims largely depends on the operation parameters of colliders and the specific structure of detectors. Within the energy range of BEPC, Time-of-Flight counter is also an important detector to make time selections. In this energy range, the events, whose final state is completely neutral, make up about 2% of all events. It should be selected. But this is not necessary for higher energy colliders where the final state multiplicity is very high. The cycles of most colliders are very long, allowing enough time for the trigger to make selections. However, in BEPC, the period is only 800 ns. After the drift time of the shower counter, the total delay of cables and various circuits and enough width of reset pulse are deducted. There is only 100 ns left for trigger in a period.

To decrease dead time, the trigger consists of several decision levels. The system is the fastest at the first level. It finishes its decision within one colliding period. If the event cannot pass the first level, the read-out electronic system and trigger are reset soon, ready to accept the next colliding event. The first level does not cause any dead time. The rate of passing first level is (1-2) kHz. These events will be selected in more detail in the second level. The event will enter the third level if it passes the second. The rate of passing the second level is (10-30) s^{-1}. The second level decision

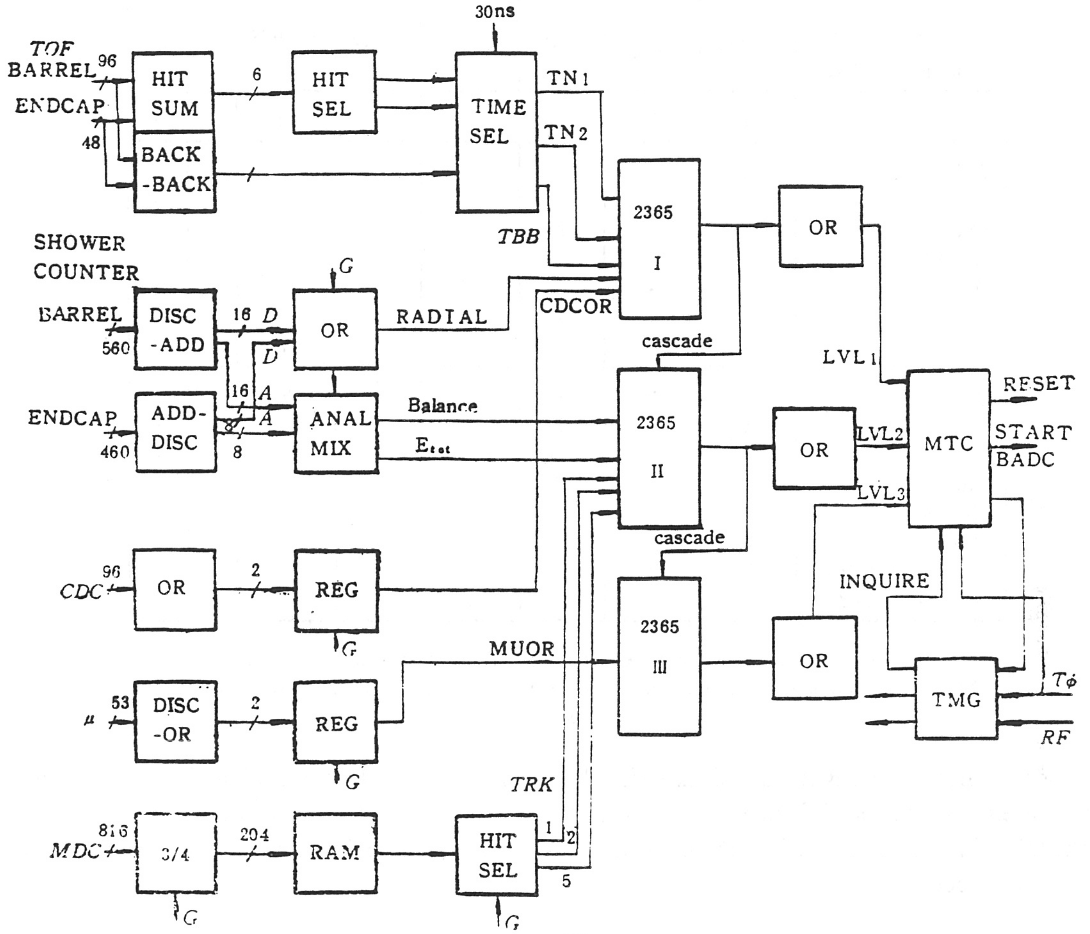

Fig. 2
The block diagram of BES's trigger.

occupies the second colliding period, causing 0.1% dead time per second. The number of periods at the third level can be adjusted according to demands. If the event cannot pass the third level, it is reset soon. The event which passes the third level is considered as a "good event". Then BADCs start A/D conversion and the online computer is instructed to be prepared for reading. After the computer finishes reading, it instructs the trigger to reset the read-out electronics to accept new events. The dead time spent on the conversion, read-out and recording of good event is about 10-20%.

Fig. 2 is the block diagram of the BES trigger. In the sense of pattern recognition, the trigger can be divided into two parts: feature extraction and decision making. Every kind of detectors in BES has its own correspondent trigger circuit. This circuit treats signals from the detector, then sends out some signals (trigger conditions) which represent certain features of events. These signals are sent to the master circuit of the trigger. Decisions are made there according to the trigger condition table

Table 1

The trigger condition table.

Condition \ Type	Bhabba	Charge	$\mu^+\mu^-$	Neutral	Spare	Cosmic ray	Spare	
Used in run	Y	Y	Y	Y	N	N	N	N
TBB	Y	-	Y	-	-	-	-	Y
TN1	-	-	-	-	-	Y	-	-
TN2	Y	Y	Y	-	Y	-	-	Y
RADIAL	Y	-	-	Y	-	-	-	-
Neutral veto	-	-	-	N	-	-	-	-
Spare	-	-	-	-	-	-	-	-
Spare	-	-	-	-	-	Y	-	-
N_{trk}^{1}	Y	Y	Y	N	-	Y	-	Y
N_{trk}^{2}	Y	Y	Y	N	Y	-	-	Y
N_{trk}^{5}	N	-	N	-	N	N	-	-
μ-or	-	-	Y	N	Y	Y	-	-
CDC-or	Y	Y	Y	-	-	-	-	Y
BALANCE	-	-	-	Y	-	-	-	-
Total energy (low)	Y	Y	-	Y	-	-	-	Y
Total energy (high)	Y	-	-	Y	-	-	-	-

Note: Y: the condition must be met for the events of corresponding types;
N: the condition must not be met for the events of corresponding types (anti-coincidence);
- : irrelevant.

(Table 1). Various time makers and gate signals are also sent out by the timing circuit to control read-out electronics and the trigger. Some scalers supervise the performance of the spectrometer. In the following part of the article, the physical considerations and realization methods of the trigger will be described.

2. THE CIRCUIT OF THE TIME-OF-FLIGHT COUNTER (TOF)

The TOF counter of BES includes a barrel of $\phi 2.89 \times 2.84$ m (48 plastic scintillators, two-end read-out) and two endcaps in the east and west (each has 24 trapezoidal scintillators, single-end read-out). Secondary particles are created from the collisions between positrons and electrons. Calculation was made for the flight time t_{of} for these particles with different momentum and mass to fly from the colliding point to the barrel TOF counter [2]. Fig. 3 shows the range of t_{of} for various particles. According to Fig. 3, if a 30-ns time window is set (i.e., t_{of} from 3-33 ns after collision is selected), the TOF counter can record all positrons and electrons, all π mesons, almost all the K mesons and most protons which hit it. The calculation also shows the time (t_{1p}) needed for the process in which secondary particles emit from the colliding point and hit the TOF counter, and in which photo pulses are generated and transmitted to the interface between plastic scintillators and the light pipe. In Fig. 4, the slanting line area means the acceptance of TOF without time selection; the ashed line and solid line areas indicate low limits of acceptances for three kinds of particles if 30 ns time window is set to t_{of} or t_{1p}, respectively. Fig. 3 shows that there is almost no difference in acceptable momentum

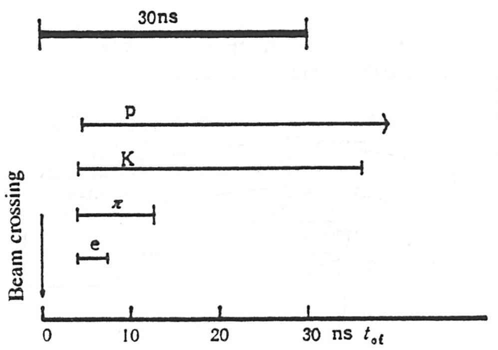

Fig. 3
The flying time ranges of the particles hitting the barrel of TOF.

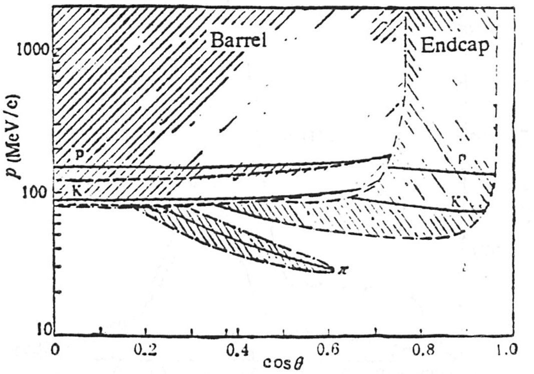

Fig. 4
The acceptance of BES's TOF.

ranges when we use t_{of} or t_{1p} for time selection. However, the former needs many expensive time averages while the latter only needs to 'OR' two signals from both ends of each counter. Because of the single-end output in TOF endcap counters, t_{of} cannot be measured. So we decided to use t_{1p}. After each collision, a 30-ns width gate is used to perform time selection for 144 discriminative signals. This can reject 96% of the cosmic ray background irrelevant to beams. In addition, we use bȧck-to-back coincidence and a 15-ns gate to select possible Bhabha events and dimuon events. This back-to-back coincidence is also used in cosmic ray runs to select cosmic ray which penetrates the center of the spectrometer. But the width of the gate is adjusted to 50 ns.

Fig. 5 shows the delay coincidence curve of TN1 (TOF counter's hit number TN1 $\geq$ 1) and TBB (back-to-back coincidence). The flat part is thought to be caused by hits of beam gas background and synchrotron radiation on the counter. A 30-ns time gate is set at the peak of back-to-back coincidence count rate. Expected Bhabha events are detected in real runs.

3. MAIN DRIFT CHAMBER AND TRACKING LOGIC [3]

The main drift chamber of BES is a cylindric detector of $\phi 230 \times 220$ cm surrounded by the TOF counter. It contains 10 layers. Each layer has 48-108 cells with four signal wires in each cell. The wires in odd layers are stereo, while the others in even layers are axial. Charged particles created in the positron and electron collision are deflected in axial magnetic field. The projections of their orbits in $R-\phi$ lane are arc-shaped and pass through beam axis. The tracking logic uses 816 signals from the inner four layers of the main drift chamber to select charged particles which emit from beam axis with curvature radius greater than 83 cm (this corresponds to transverse momentum $p_t \geq 100$ MeV$/c$ in 0.4 T magnetic field). Then we can reject 95% of the cosmic ray background in space aspect and 99.9% background relevant to beams in p_t aspect. We choose the signals from the inner four layers to do the tracking, so that the solid angle it covers matches the one of the TOF counter, and meanwhile there are enough hits to determine a track. At first 204 × 4 signals are sent to 3/4 logic modules [4]. If there are three or more wires fired in a cell, it is believed that there is a hit at this cell. This method not only avoids a false track caused by random fire background in the main drift chamber, but also reduces losses caused by wire inefficiency. Then 204 hit signals are sent to RAM

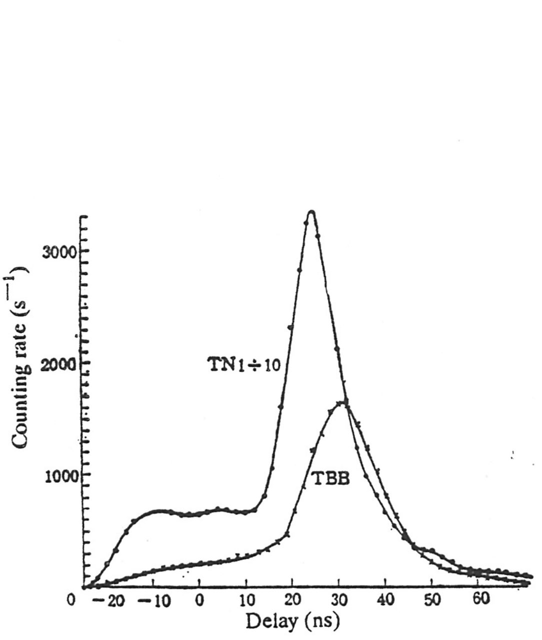

Fig. 5
The delay coincident curves of trigger signals of BES's TOF.

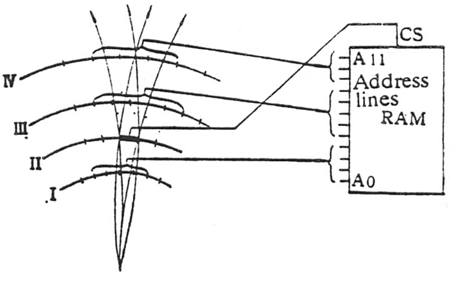

Fig. 6
The principle figure of the track finding circuit of MDC.

modules in order to decide whether they constitute a good track. All the possible combinations of cell numbers in layers I, II, III and IV which form a good track are stored in 12 RAM modules (Fig. 6). The 204 hit signals are used as address to check if this is a good track. Finally, four tracking signals of this event ($N_{track} \geq 1, 2, 3$, and 5) are obtained by using LRS4448 coincidence register and summing discriminators, and are sent to the master trigger.

Good track combinations are loaded into RAM modules through CAMAC before each run. So if any alternation of transverse momentum cut p_t or magnetic field is required, only new good track combinations need to be loaded. No change in the hardware and cables is necessary.

The Monte-Carlo simulation shows that if the shortest distance r_0 from a track to beam axis is longer than 12 cm, the probability of mistaking it for a good track is less than 25% (Fig. 7a); and if the longitudinal distance z_0 of the track to the colliding point is longer than 106 cm, the mistake probability is less than 50% (Fig. 7b). Fig. 7a shows the relationship between the efficiency in recognizing good tracks that emit isotropicly from the colliding point and the track transverse momentum. The conclusion shown in Fig. 7a is proved by the fact that all the tracks selected by the tracking circuit and the back-to-back coincidence of TOF counter pass through the central drift chamber.

Because the longest drift time in MDC is up to 600 ns, the tracking logic has to be put into the second level of the trigger. There are some substitute registers in 3/4 logic modules. If a certain cell goes wrong, the bit in the register corresponding to that cell is set to '1'. This prevents the loss of trigger efficiency caused by the cell's breakdown. The substitute registers can also be used for checking the tracking logic with the computer.

4. THE TRIGGER CIRCUIT OF THE SHOWER COUNTER

The shower counter (SC) of BES is a sandwich gas energy sampling calorimeter located outside the TOF counter. It includes two parts, barrel and endcaps. The barrel is shaped like a cylinder, with

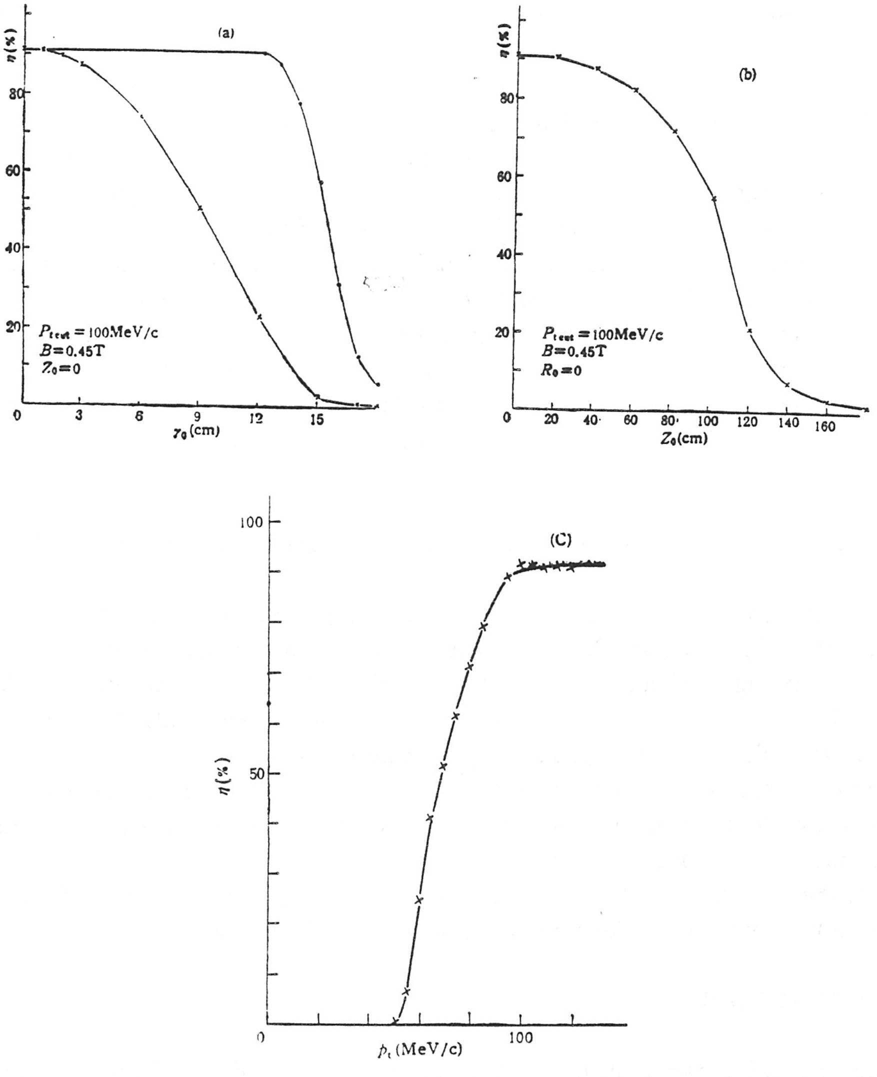

Fig. 7

The Monte-Carlo simulation of the track finding circuit of MDC.

—•—•—: the rate passing 3/4 logic; —×—×—: the rate passing the track finding logic.

an internal radius of 247 cm, an external radius of 338 cm and a length of 385 cm. It is divided into 560 cells along the ϕ direction, and each cell contains 24 layers along the radius. 24 wires are ganged in 6 output signals. Every two cells is called a wedge (Fig. 8). SC trigger circuit is used to perform energy selection for charged particle events, and to select the events whose final state contains only neutral particles. Photons do not deflect in magnetic field. The elector-magnetic shower they cause in the shower counter develops along the radius. If the amplitude of 12 signals in a wedge exceeds the discrimination threshold, it is thought that there is a shower developing along the radius. We use this method to reject the cosmic ray which penetrates shower counter obliquely. All wedge signals added from the 12 signals in a wedge are further added to form quadrant signals. We use quadrant signals to judge the energy balance of events. Finally, we add quadrant signals to the total energy signal in order to perform discrimination to reject background with low energy, such as synchrotron-radiation, etc.

Shower counter uses 24 Fan-in discriminator modules to discriminate and linearly add the 1020 wedge deposition energy signals obtained in front of the sample hold circuit. The logic signals are sent to a logic module to be 'OR'ed into a 'RADIAL' condition signal. It takes part in the first level of the trigger. Analogy output signals are sent to an analogy modules for further processing. It gives signals of the energy 'BALANCE' condition and total energy condition. These two signals take part in the second level decision. In the barrel, energy balance conditions require quadrant-quadrant coincidence along the ϕ direction; in endcaps, they require eastern-western endcap coincidence. In addition, there are eastern barrel-western endcap or western barrel-eastern endcap coincidences. Total energy conditions have a high threshold and a low threshold. The high threshold is used to select Bhabha events and neutral events, while the low threshold is used to select charged particle events. Except that of deposition energy in a wedge, thresholds of other analogy signals can be set by computer.

5. THE TRIGGER CIRCUIT OF THE CENTRAL DRIFT CHAMBER AND μ IDENTIFIER

The central drift chamber, located between the beam pipe and the main drift chamber, is a cylinder with an external diameter of 29.6 cm and a length of 110 cm. It contains four layers and each layer has 48 cells. The trigger circuit of central drift chamber 'OR's 96 discriminated signals from layers 3 and 4 and latches the results (layers 1 and 2 have too much background). It is used to select charged particles and reject most background in space aspect (r and z directions).

The μ identifier is the outmost detector of Beijing Spectrometer. Its trigger circuit discriminates and 'OR's 53 analogy-added signals, and latches the results to mark the muons which penetrate the shower counter and solenoid magnetic iron.

Because of the long delay of the sample and hold circuit of μ identifier, 10% of the signals arrive after the second level. So the decision of μ is made on the third level.

6. THE MASTER TRIGGER

The master trigger is a part of the trigger that makes decisions and classifications (see Fig. 2). All the signals of the above-mentioned features are collected and sent to it. They are determined according to the trigger condition table (Table 1). The table is interpreted into 18×3 control words. These words are loaded into three LRS 2365 modules before every run. LRS 2365 [7] is a programmable 16×8 matrix logic module. It can make 8 different combinations of 16 signals according to the loaded control words and give 8 logic outputs. So we can select up to 8 different types of events at the same time. The trigger condition table can be changed flexibly according to the demand as to the types to be selected and the conditions to be met, etc. 8 output signals of each LRS 2365 are 'OR'ed and then sent to the master trigger control module (MTC). This means that the required condition of at least one type of events is satisfied at that level. MTC strobes at 420 ns 'INQUIRE' in the corresponding period. If there is 'OR' signal at this time, it will enter next decision level or send out a 'good event' signal. If none of the conditions of any event type is satisfied at this level, a reset signal will be sent out after 'INQUIRE' to reset all the read-out electronics and the

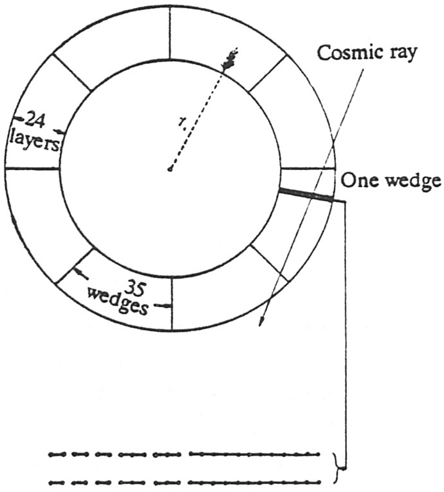

Fig. 8
The principle of radial decision of barrel of shower counter.

trigger, having them ready to accept the next event. As for a 'good event,' we can learn which type of events it may be or which condition is satisfied by reading the outputs and inputs of LRS 2365. These messages are displayed on the one-event-display.

When operating in a non-resonance area, because Bhabha events are much more than any other events, prescale of Bhabha events is necessary. It means that to Bhabha events, only one 'good event' signal is sent out for every N_{bb} Bhabha event. This function is implemented in MTC.

In the master trigger, the delay between the input of trigger condition signals and the output of a 'good event' signal is 45 ns. The trigger issues reset signal at a fixed moment during a period. It helps each sample and hold circuit keep fixed pedestals.

7. TIMING CIRCUIT

Because all the good events follow e^+e^- collisions, the read-out electronics and trigger of Beijing Spectrometer should work synchronously with beam collisions. By using the beam crossing signal as a time reference (T_0) and the 200 MHz high frequent signal RF of storing ring as a synchronous clock, three time-marker generators (TMG) generate some time markers with a width of 10 ns and gate signals with a given width at proper moments to read-out electronics and the trigger in order to make them operate synchronously. The width and front edge of every signal are programmable. In a cosmic ray run, a 100 MHz local crystal oscillator is used as a clock and a 'period' signal set in TMG2 as T_0, respectively.

8. SCALER

Besides recording on tape the good events which satisfy trigger conditions, we should monitor the counting rates of various signals produced in the process at each decision level, such as the trigger condition signals of each trigger level, the rate of passing each level of the trigger and the dead time. These messages are not included in the output of good events. So we installed two sets of scales: one, in CAMAC, is used to read data and record on tape periodically by online computer, so that dead time can be calibrated. The other, installed in the control console, is used to display various counting rates on real time. Through these counting rates, we can determine whether the collider and detectors are operating normally and whether each discrimination threshold is proper, and improve the trigger table accordingly.

9. SUMMARY

We made physical and logic design for the trigger of BES and completed 41 kinds of specific modules. System check was done with IBM-PC/XT and VAX-785 before and after general assembly. We measured the delay of every part of trigger and read-out system of the whole spectrometer, determined the value of each time maker and the trigger condition table, and succeeded in the cosmic ray run (Oct. 1988) and colliding run (May 1989). We further improved the trigger condition table, suppressed cosmic ray background to 0.1 s^{-1} and beam-related background to 0.4 s^{-1} at J/ψ colliding energy and kept J/ψ event rate at 3 s^{-1}. In addition, we realized the trigger decision of neutral event in April 1990. The correctness of the trigger design has been proved and its flexibility and stability are displayed in practical runs.

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