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LHCb Preshower Signal Characteristics

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Abstract

Time structure of the pulse shape in preshower cells is experimentally investigated using various light sources: electron beam and cosmic rays. They produce typical signals and provide a large dynamic of deposited energy. In addition performances of the multianode R5900-00-64 PMT which is a candidate for the light read-out system are also studied with regard to saturation. The question of the preshower dynamic range useful for trigger and physics is also addressed together with the influence of cross-talk among preshower cells. This effect is important for calorimeter trigger.

1 Introduction

Specifications of the preshower front-end electronics rely on tasks dedicated to this detector:

- Provide for each of the 6000 cells a 40 MHz trigger signal contributing to the calorimeter level 0 trigger. A threshold at the 5 MIP's level is applied to the signal integrated on a time range less than 25 ns. The low energy signal (about 1 MIP) will be also used for calibration.
- Correct ECAL measurements in the range of low energies.

Thus performances of the preshower measurements have to be investigated in detail at both ends of the energy range. In practice a 1 MIP signal corresponds to about 30 photoelectrons out of the PMT photocathode and the pulse shape of such a low signal should be measured. This was done using cosmic rays tests. Preshower requirements for large energy electrons were both studied with test beam data and with other data taken from ALEPH experiment. Read out of light from scintillator cells by the 64 channels PMT R5900-64 has also to be looked at in more details mainly for what concerns saturations and cross-talk. All the studies on this subject will be summarized in this note.

2 Preshower signal pulse shape

Pulse shape of a preshower cell can be computed in a basic way and refined by Monte Carlo simulation to introduce stochastic phenomena. In this approach the shape of the pulse observed at the end of the wavelength shifter fiber is computed assuming that the original fluorescent light is homogeneously produced along the fiber after the capture of the scintillation light. In addition, the simple assumption that the original scintillation light is catched instantaneously in the wavelength fiber at t=0 is done. Then a photon resulting from fluorescence will arrive at a time

$$t = t_0 + t_{des}$$

where t_0 is the light propagation time from the site of fluorescence to the end of the fiber; t_{des} is the moment at which the desexcitation takes place and produces the fluorescence photon: this one will be assumed to be distributed according to only one exponential. In the analytical part of this computation, the speed of the light component orthogonal to the fiber axis is neglected. If L is the fiber's length and v the speed of light in the fiber, L/v is the maximal value of the propagation time t_0 .

The desexcitation time t_{des} is distributed according to an exponential law

$$e^{-(t-t_0)/T}$$

where T is the fluorescent time. Then the pulse shape can be given by two expressions depending on its value with respect to a time characteristic of the fiber length: • For time t smaller than L/v:

$$P(t) = \int_0^t n(t_0) exp(-\frac{(t-t_0)}{T}) dt_0 \propto 1 - exp(-\frac{t}{T}) x$$

where $n(t_0)$ is the distribution of photons along the fiber (assumed here to be constant). • For t larger than L/v the pulse shape is simply distributed according to

$$P(t) = \int_0^{L/v} n(t_0) exp(-\frac{(t-t_0)}{T}) dt_0 \propto exp(-\frac{t}{T})$$

Several additionnal inputs can be added in such an analytical calculation. In practice Monte carlo simulation is more efficient and was used. The interest of this first computation is simply to show the respective importance of the fiber length and of the desexcitation time. Up to the total propagation time the pulse shape is mainly 1-(exponential desexcitation). For t larger than this total propagation time this is simply a decreasing exponential.

More realistic aspects in production, propagation, attenuation and conversion of photons to produce the signal out of the phototube are incorporated in a Monte Carlo simulation program, but do not modify drastically the shape obtained by the simple analytical computation.

•**Production of fluorescence photons**. This one is generated with an exponential decay law with the constant time of the fiber (10 ns for the Y11).

•**Propagation**. The length of the fiber is fixed by the definition of the helix parameters (diameter = $2./3.\times$ cell size, number of turns in the tile thickness: 5 in this version which means a fiber length of the order of 1.25 meters). The speed of light is given by the refraction index (here n=1.59 which means 5.3 ns/m). The fact that photons do not propagate along the fiber axis is taken into account; for a photon below the total reflexion limit this can produce a total propagation length up to 5 times larger than the nominal one while most of the photons have a path increased by less than 20 %).

• Attenuation in the fiber. This physical parameter is not negligible for the time pulse shape. This is simulated according to the measured curve for the Kuraray Y11 fiber as shown on figure 1.

• Conversion in the photocathode. At the moment this is simply a global efficiency. In fact this is a raw approximation since it is dependent on the wavelength associated to the photon. For the photons with a large propagation length, the average wavelength is closest to the green than those originating near to the photocathode (due to attenuation). This could be a source of distorsion of the pulse shape which at the moment is not introduced.

• **Phototube**. For each photoelectron out of the photocathode, the gain of the phototube is simulated in the following way:

- The average gain of each 10 dynodes is computed according to the total gain of the tube: of the order of 4 for a total gain of 10^6 .

- The cumulative gain of the dynodes is computed taking into account a statistical fluctuation of the gain at the dynode level given by a Poisson law.

- The photoelectron time arrival on the anode is generated according to the shape provided by Hamamatsu (we use a R5900 with no green extended photocathode).

The used preshower cell was a scintillator tile with a size of $40 \times 40 \text{ mm}^2$ and with a deep grooved machined inside it. The fiber was coiled inside the cell in "spiral" and was read out by both ends. Its lenght was of the order of 1.25 m. Figures 2 and 3 show that data and simulation give a similar shape for an average signal.



Figure 1: Light attenuation as a function of length



Figure 2: Average signal for cosmic ray (left) and simulation (right)



Figure 3: fraction of signal after 25 ns on data (up) and monte carlo (low)

In practice 1 MIP signal is very eratic (figure 4) due to the small number of corresponding photoelectrons; this explains the large dispersion observed for the fraction of total signal measured after 25 ns (figure 3). This statistical dispersion is clearly reduced when looking at a 5 MIP signal which corresponds to the threshold applied for triggerring on incident electrons (figure 5). This figure shows that 85 % of the signal is integrated after 25 ns. The statistical fluctuation of 4% is the size of the Least Significant Bit (LSB) set at 1/5 MIP.

3 Signal from electrons

After exposing a preshower cell to a MIP, it was studied in a test beam with 20 and 50 GeV electrons. Light was read out by a 64 channels R5900-00-M64 Hamamatsu phototube which is a candidate for the final design. It has 12 stages and a photocathode segmented in 64 pixels of $2 \times 2 \text{ mm}^2$ each. Its voltage distribution ratio is 3-2-2-1...1-2-5 and designed by the firm for improved linearity. Figure 6 shows 6 typical individual signals from 50 GeV electrons. This indicates that the larger is the amplitude, the broader in time is the signal. This is confirmed on Figure 7 where an average shape of the signal is given by slice of amplitudes.

This is not dependent on the original energy of the electron and the same shape is observed with 20 GeV electrons. This is the sign of a saturation. This one is expected to occur with the R5900-00-M64 phototube operating with a gain of 3×10^5 on a pulse of 100 photoelectrons on a pixel of the PMT. This implies that a correct running will

Signals



Figure 4: various 1 MIP signal in a preshower cell

Fraction of the 5 MIP Signal in a Range of 25ns (Data)



Figure 5: Fraction of a 5 MIP signal after 25ns



Figure 6: Pulse shape in the preshower produced by 50 GeV electrons



Figure 7: Average pulse shape in the preshower produced by 50 GeV electrons by slice of amplitude (decreasing up to down and left to right)

require low value of the PMT high voltage power supply. This was further investigated by exciting the PMT by a LED.

4 Signal induced by a blue LED

In the front-end electronics [1], PMT signal goes through a load resistor to produce input signal of the integrator. For the presented measurements the output signal of the PMT attacked a CLC400 with a resistor R_0 which was varied from 50 to 250 Ω corresponding to the expected range for the final design. The Hamamatsu R5900-00-64 PMT was illuminated by a blue LED short pulse shown in Figure 8 and PMT High voltage was increased from 650V (figure 8) to 800V (figure 9). The pulse out of the PMT is shown for these two HT values and demonstrates a clear increase of light collection time. Let's



Figure 8: Blue LED pulse shape and shaper pulse out signal with a 50 Ω load resistor and 650 V high voltage

notice that the slight shift in time of the shaper output between figure 8 and figure 9 is due to faster answer of the PMT with HV increase. For all these measurements only one channel among the 64 is connected. Shape variation with HV looks like a saturation of the PMT channel: this will be confirmed by amplitude measurements shown in next section. At that time we are interested to look at the effect of increasing the resistor load value in order to adapt the signal amplitude to take advantage of the full range of the ADC but also to adapt the channel by channel resistor load to smooth intrinsic gain variation from one PMT channel to the other. Figure 10 shows modification of the output pulse shape when the load resistor is increased from 50 Ω to 250 Ω ; in the same time the maximum amplitude is only increased by a factor 3.5 instead of 5 which indicates clearly the effect of various parasitic capacitors. We then decided not to use load resistors larger than 250 Ω .



Figure 9: Blue LED pulse shape and shaper pulse out signal with a 50 Ω load resistor and 800 V high voltage



Figure 10: Shaper output signal with 50 Ω and 250 Ω . The former is the first signal on the left with a vertical scale off 10 mV on the scope. The latter is the less noisy signal on the right. The other pulse is irrelevant

5 Looking at saturation

The shaper load resistor is fixed to 250 Ω and PMT high voltage is increased from 508 V to 737 V by step of about 35V; this HV step corresponds to about a factor 2 in PMT gain. A 1 mV residual oscillation remains superposed to the signal. Figure 11 shows shapes and amplitudes of the signals for the various voltages.



Figure 11: Signals out of the shaper with 250 Ω load resistor and 7 HT values: 507V, 537V, 571V, 608V, 665V, 700 V, 737V. Horizontal scale is ns, vertical scale is volt

Looking at these pulse shapes in more detail shows clearly that they are modified when HV increases. This effect increases dramatically when HV becomes larger than 700V. Figure 12 shows this shape distorsion: amplitudes maxima are normalized and time offset are included to compensate the different drift times in the PMT for various voltages.

Three plots are given on figure 13. High left corner shows the value of the maximum of the signal in Volt versus the integral. This shows that for larger signals we lose linearity; in all the biplots of figure 13 one point is given for each high voltage listed on figure 11. Figure 13 high right gives the value of the maximum versus high voltage. It confirms that saturation appears for a high voltage around 700 V. Saturation is almost not visible on the integral signal (figure 13 low left).

In practice saturation depends on the photo electron flux out of the photocathode and on the PMT gain (7.5×10^4 at 700V). In the current case, we have estimated the p.e. flux at the photocathode to about 600. If we work with an high voltage value of 600V (gain 1.6×10^4) we can accept signal as large as 2800 p.e. out of the photocathode. This corresponds to a signal of the order of 50 to 100 MIP depending on the light collection in one cell of the preshower. Let's notice that we operated here in the worse situation from



Figure 12: Comparison of pulse shapes at 571V and 737V (dashed line on left and right plots respectively) to pulse shape at 507V (solid line). Pulse are normalized by there maximum amplitudes



Figure 13: Upper left: maximum of the pulse versus integral; upper right: amplitude versus high voltage (log/log); lower left integral versus high voltage (log/log)

the point of view of saturation since the light flux out of the LED is very short (about 5 ns) with respect to the situation of the LHCb preshower (more than 15 ns).

6 Dynamical range of preshower signals

The dynamical range of Preshower signals have been investigated from data collected in the Aleph electromagnetic calorimeter [2]. Energy depositing from electrons up to an energy of 100 GeV have thus been studied using a sampling of the ALEPH calorimeter [3] that simulates the LHCb Preshower+ECAL layout. The first ALEPH ECAL layers up to $2X_0$ have been used to simulate the *Preshower* and the last ones to simulate the *Ecal*.

The longitudinal behaviour of shower inside this *simulated Preshower* and ECAL is studied using three energy ranges of electrons :

i) high energy range : ~ 90-100 GeV electrons from Bhabha events or Z^* decay at LEP 2 ii) medium energy range : ~ 45 GeV electrons from Bhabha events or Z decay at LEP 1 iii) low energy range : ~ 5 GeV electrons from $\gamma\gamma$ collisions.

The *"minimum ionizing particle"* (MIP) signal is defined from 1-3 GeV identified muons. The MIP unit is chosen to be the mean value of the averaged energy deposition per layer.



Figure 14: Muon (dashed) and electron (solid) "Preshower" signal in MIP unit for 5 GeV (a), 45 GeV (b) and \sim 95 GeV (c) electrons. The 95 GeV electron signal extends to about 200 MIP units. Note the logarithmic scale on the two axis.

Figures 14(a), 14(b) and 14(c) display the muon and electron *Preshower* signal distributions in MIP units for 5 GeV, 45 GeV and 95 GeV electron respectively.

Preshower signal from 100 GeV electron has its most probable value between 30 and 40 MIP units and extends up to about 200 MIP units. Assuming that the fraction of MIP unit assigned to the Least Significant Bit (LSB) is $\frac{1}{5}$ MIP, this 0.2 to 200 MIP units dynamical range can thus be encoded within 10 bits with negligible saturation for electrons up to an energy of about 100 GeV.

The fraction of events that saturates a 10 bit dynamics is displayed in figure 15 as a function of the MIP channel (n^{th} channel corresponds to $\frac{1}{n}$ MIP for the LSB).

With the LSB set to $\frac{1}{10}$ MIP, a 10 bit dynamical range is sufficient to collect with



Figure 15: Fraction of 95 GeV (solid), 45 GeV (dashed) or 5 GeV (dot-dashed) electrons that saturates a 10 bits dynamic range in function of the MIP channel. The nth channel corresponds to $\frac{1}{n}$ MIP for the LSB. For the LSB corresponding to $\frac{1}{10}$ MIP, 8% of the 95 GeV electrons saturate the dynamics.

negligible saturation the preshower energy from electrons up to 50 GeV energy. This will allow preshower calibration with MIP.

7 ECAL energy correction with preshower

The Preshower materials degrades the Ecal performances. However, this can be compensated when Preshower and Ecal energy measurements are combined.

The energy measurement resolution applying preshower compensation has been studied using ALEPH data [2].

As can be seen on figures 16, the mean energy fraction deposited in the $2X_0$ Preshower thickness respectively is 6.0%, 1.5% and 0.9% for 5 GeV, 45 GeV and 95 GeV electrons, Consequently, an actual Preshower correction is not expected to improve significantly the Ecal energy resolution for high energy electrons. Figure 17(a) shows linear fits of the energy resolution $\frac{\sigma_E}{E}$ with and without the Preshower correction as a function of $\frac{1}{\sqrt{E}}$. The Preshower correction clearly improves the energy resolution of low electrons energy. For 100 GeV electrons the resolution is essentially the same with and without Preshower



Figure 16: a) Energy deposition in the Preshower (GeV) versus the energy deposition in the Ecal (GeV) for a 2 X_0 thick Preshower.

b) Fraction of the incoming energy deposited in the Preshower versus the energy deposition in the Ecal (GeV) for a 2 X_0 thick Preshower.



Figure 17: (a) Fit of the energy resolution according to $\frac{\sigma_E}{E} = \frac{\alpha}{\sqrt{E}} + \beta$ with (solid) and without (dashed) Preshower correction. $A \sim 3$ GeV electrons sample has been added in order to improve the fit accuracy.

(b) Relative improvement of the energy resolution as a function of energy when actual Preshower correction is added. The light band indicates the level of uncertainty estimated by varying the fits parameters inside $\pm 1\sigma$ and assuming the slope of the two fits are fully correlated.

correction. The relative resolution improvement $\frac{(\sigma_E/E)_{Ecal} - (\sigma_E/E)_{PS+Ecal}}{(\sigma_E/E)_{Ecal}}$ is displayed on figure 17(b) as a function of the energy.

From figures 15 and 17 (b) it is seen that there will be saturation in 5% of events for 45 GeV electrons and that the effect on the electron energy resolution will be negligible. As a baseline solution, a calibration corresponding to LSB equal to $\frac{1}{10}$ of a channel is therefore adopted.

8 Impact of pulse overlap on preshower signal reconstruction

Front-End electronics of LØ-pipeline is clocked at 40 MHz. However, the preshower pulse duration is typically longer than the 25 ns separating two consecutive LHC bunchcrossings. As a consequence, only a fraction α of the pulses lies within 25 ns. The Preshower Front-End electronics will thus integrate the pulse shape over 25 ns, digitalize it and apply a preceeding pulses correction [4]. Because of the event-by-event dispersion of the various contributions to the measured pulse, the energy measurement resolution is limited. More important effect could arrise in case of preceeding pulse saturating the ADC dynamics [5].

The impact of preceeding pulse on the occupancy rate of the preshower and on the probability for a cell to be hit twice consecutively with a large preceeding pulse are shown in figure 18.

Using overlapping parameters (mean integrated signal fraction $\alpha \sim 80\%$ and dispersion $\delta \alpha \sim 10\%$ corresponding to 20-30 photo-electrons per MIP) obtained from cosmic bench test [4], a precision of 0.3 MIP is obtained when reconstructing 5 MIP units signals. Assuming the LSB is set to $\frac{1}{10}$ MIP, the Front-End electronics digitization contributes at the level of 0.03 MIP.

The corresponding wrong trigger rate is typically $\mathcal{O}(0.5\%)$ of the triggering events with $E_T^{cluster} > 1$ GeV. Because of the low probability for a cell to be hit twice consecutively this wrong trigger rate is essentially induced by the event-by-event dispersion of the current pulse integrated fraction. The rate is unlikely affected by poorly subtracted preceeding residuals and *a fortiori* by an eventual 10 bits dynamics saturation.

Assuming more pessimistic choice of parameters (larger overlapping fraction α , larger event-by-event dispersion $\delta \alpha$, higher multiplicity event, higher luminosity, smaller $E_T^{cluster}$ trigger threshold ...), the wrong trigger rate increases up to the few percent level (see figure 19).

The previous results assume an exponential behaviour for preshower pulses. Multiexponential behaviour, strong non-linearity or saturation of the photomultiplier response could also affect the signal reconstruction by Front-End electronics. Such pulse shape distortions and their possible impact on preshower performances have *not* been considered here and are addressed to experimental studies of preshower pulses.



Figure 18: Upper : Mean number of fired preshower cells with signal s_t greater than x as a function of x (in MIP unit) for $\mathcal{L} = 2.10^{32} cm^2 s^{-1}$ (full lines) and $\mathcal{L} = 5.10^{32} cm^2 s^{-1}$ (dashed lines). The contribution of cells actually not hit during the current bunch-crossing but receiving preceeding bunch-crossing residual pulse is indicated as "Residuals".

Lower : Mean number of preshower cells hit twice consecutively with a preceeding signal s_{t-1} greater than x as function of x (in MIP unit) for $\mathcal{L} = 2.10^{32}$ (full lines) and $\mathcal{L} = 5.10^{32} cm^2 s^{-1}$ (dashed lines).

Only single interaction bunch-crossings leading to at least one electromagnetic LØ-trigger cluster with $E_T^{cluster} > 1$ GeV are considered on both figures. Vertical full lines respectively indicate the upper limit of 10 bit dynamical range assuming the LSB is $\frac{1}{5}$, $\frac{1}{10}$ and $\frac{1}{20}$ MIP.



Figure 19: Rate of wrong (lost or fakely triggering) trigger action affecting single-interaction bunch-crossing with at least one electromagnetic LØ-trigger cluster ($E_T^{cluster} > 1$ GeV) as function of $\delta \alpha$ for α values varying from 90% to 60%. Full and dashed lines respectively correspond to the low ($\mathcal{L} = 2.10^{32} cm^2 s^{-1}$) and high ($\mathcal{L} = 5.10^{32} cm^2 s^{-1}$) luminosity hypothesis.

9 Impact of Cross-Talk on preshower signal reconstruction

The preshower signals are extracted from scintillator cells using bundled fibres. Cross-talk between fibres inside the bundle, at the coupling stage of the bundle to the multi-anode photomultipliers or inside the photomultiplier results in the fact that a preshower signal can contribute to several channels. This feature limits the measurement precision and the trigger task of the preshower.

The main source of cross-talk is due to the light spot from fibers spreading, on the photocathode, after traversing the phototube entrance window, over an area larger than the $2 \times 2 \text{ mm}^2$ pixel area. Within simplifying assumptions, cross-talk between PS cells has been simulated.

Assuming a 20% level cross-talk distributed among the 8 adjacent preshower cells and a 30% event-by-event relative dispersion, a corrected 5 MIP units signals is measured with a 0.5 MIP accuracy.

If, as proposed in [6], a veto is implemented on electron or photon trigger candidates, when 3 or 4 preshower cells in front of the ECAL cells are above threshold, then the lateral cross-talk described above can decrease the efficiency of the trigger. The effect is calculated to be of the order of 10% of the trigger rate, for 20% cross talk. This veto leads to reject most of the large E_T electromagnetic clusters. Whithout the veto requirement, the remaining effects of cross-talk are at the 1% level. This does not exceed the 2-3 percent level even for cross-talk as large as 40% of signal values. Adding cross-talk between SPD cells or increasing the event-by-event dispersion to 50% relative does not increase significantly the wrong trigger rate.

Wrong trigger rate, induced by cross-talk, is defined as the fraction of triggering events that are lost (clusters above threshold are lost) or fakely triggered (clusters above threshold are fake) when adding cross-talk and it is displayed on figure 20 as a function of cross-talk level. More details can be found in reference [5].



Figure 20: Wrong trigger rate as function of the cross-talk level and for different combinations of E_T thresholds : 1, 2, 3 GeV for both "electron" and "photon" cluster candidates. Full and dashed lines respectively correspond to the use of the veto condition or not.

Studies will continue on how to decrease the cross-talk (by better optical segmentation). If no solution is found, the veto condition could be removed which would worsen the minimum bias rejection by about 10 %.

10 Conclusions

Experimental study of the light signal out of a preshower cell shows that its time structure is very eratic at the level of a 1 MIP signal. This is due to the small number of photons collected for such an incident particule. Notheless, this is sufficient to be used for a trigger cut of 5 MIP as an identification of electrons. Another important conclusion is that a large fraction (about 85 %) of the light is collected within 25 ns after the particule went through the detector. Assuming the Least Significant Bit (LSB) is $\frac{1}{10}$ MIP, a dynamics of 10 bit for Front-End electronics allows to digitize without saturation the preshower signal from electrons up to 50 GeV energy. In addition, rare saturating energy deposition in excess of 10 bit dynamics has been shown to not affect the trigger task of the preshower.

Taking into account the limited precision due to the digitization, to the pulses overlap between consecutive beam-crossings and to cross-talk, the precision on a 5 MIPs signal is about 0.6 MIPs.

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