Study of Plastic Scintillator with WLS fibre and light guide

Gagan Bihari Mohanty

Abstract

We have studied light output from two types of plastic scintillators using light guide and wavelength shifting (WLS) fibres embedded in grooves of different configuration. Various comparisons in terms of spectrum and the photo-electron yield due to cosmic ray muons have been presented in this report.
Introduction

Hadron calorimeter is a crucial component for detectors in future high energy collider experiments (CMS and ATLAS) at LHC (Large Hadron Collider). It offers a unique possibilities to recognise rare events at the trigger level, and to measure the characteristics of these selected events under severe background, with a compact instrumentation. Achieving the best possible energy resolution is closely linked to the capability of observing Higgs and SUSY particles which are primary physics motivations behind the experiments at LHC. Ultimately detection of all these particles along with other interesting subjects would definitely open a new era in high energy physics refining our present status of knowledge regarding fundamental interactions in nature.

The hadron calorimeter in CMS detector is a sampling type of calorimeter of about 12 interaction deep. It consists of plastic scintillator plates interleaved with copper-plates as absorber. The light output due to passage of high energy particles during Proton-Proton interaction will be collected using WLS fibres spliced with clear fibres and ultimately transferred to the read-out system. EHEP group which is participating in CMS experiment has taken a significant role in the construction of the outer part of the hadron calorimeter (HBO) of CMS detector along with five more Indian groups. The work reported here is a part of the R&D activities going on at TIFR to examine the feasibility of detector design to provide good energy resolution, reliability etc, since HBO is an independent sub-unit of the whole detector. In particular we have studied the light output from different plastic scintillators with various light-readout techniques of optical light guide and WLS fibre.

Why Plastic Scintillator?

When an energetic particle passes through a scintillating medium, it loses a fraction of its energy which is transformed into scintillated light. In case of the plastic scintillator (an organic material), energy lost by the incident particle excites the electron in $\pi$-molecular orbitals into its excited states. Eventually on de-excitation to ground state, radiation gets emitted within a few nano-second. Typically this emitted radiation is not self-absorbed by the scintillator as the energy difference in the emission and absorption spectra don’t match. The emission spectrum has a broad range in wavelength starting from ultraviolet to near-infrared depending on the scintillator material. But the scintillation efficiency $S$ is defined as the fraction of the incident energy which is converted into visible light by the scintillator. Under the assumption that the scintillator responds in a linear fashion i.e. the visible light emitted $L$ is directly proportional to the energy deposited $\Delta E$; $S$ is given as follows:

$$S = \left( \frac{L}{\Delta E} \right)$$

(1)

Of course all other alternative de-excitation modes like lattice vibration, heat etc., which do not involve any radiation are not taken into account in equation (1).

Fast time response, good energy resolution in addition to the extra reliability and robustness provided by the plastic scintillator are the main deciding criteria of choosing it as a sensitive detector in large scale high energy physics experiment. On proper combination
with an elegant light-readout system, this becomes the best choice for sampling type of calorimeter.

**Importance of light-readout technique**

The crucial points to be considered in scintillation detector technology are those of uniformity in collecting largest fraction of the emitted light and efficiently guiding it to the light-collecting device which is a photo-multiplier tube (PMT) in most of the cases. Typically the shape and size of the scintillator are not suitable to couple it directly to the circular face of the PMT (typical diameter=5cm). Better light collection efficiency can be achieved by using an optically transparent solid of suitable shape, called *Light guide*, to physically couple the scintillator to the PMT.

Light guide operates on the principle of total internal reflection. It’s refractive index is relatively high and fairly close to that of the scintillating material. Thus the critical angle for total internal reflection is less. Also due to matching in refractive indices the probability of back-trapping of light gets reduced. Thus one gets very good light output at the photo-cathode level of the PMT.

The requirement of compact detectors with minimum dead space has led to the use of WLS fibres instead of guides which allows the PMT to be placed far away from the scintillator. Also in this way the PMT performance does not get affected by the presence of high magnetic field in the detector volume. Fibres embedded in grooves on the scintillator surface is one of the useful option for extracting light from the scintillator plate.

The basic principle of operation of the WLS fibre lay-out is that a fraction of the primary scintillation light gets absorbed by it and subsequently re-emitted isotropically at a longer wavelength. A fraction of this wavelength shifted light is then guided to the PMT via total internal reflection. In order to facilitate this, the outer cladding of the fibre is made up of a material of lower refractive index in comparison to the inner core. The overall light collection efficiency of this scheme can not be compared with that of the light-guide. But in case of CMS hadron calorimeter, there will be enough number of particles hitting the detector module so that the scintillation light yield would be large enough to allow one to tolerate considerable loss during collection process.

**Experimental setup and scintillator tested**

The experimental setup consists of mainly following sub-units
a) trigger system (Discriminator and Coincidence unit)
b) test scintillator
c) high tension power supply (0-3 KV)
d) gate generator of variable width
d) charge-sensitive ADC (0.25 pC per ADC count)
:e) CAMAC-GPIB interface unit
f) Personal Computer (for online data storage)

The trigger circuit is made by putting three trigger paddles (T1, T2, T3) of size
15cm x 18cm, 15cm x 18cm and 30cm x 30cm respectively. The distance between T1 and T3 is kept well enough (typically 30cm) to make sure that the muons passing through the paddles are almost vertical. The signals from the trigger paddles are fed to discriminator with threshold of 30mV and subsequently to the coincidence unit. The three-fold coincidence rate obtained is about 0.8Hz. The coincidence output is fed to the gate generator providing an ADC trigger gate of width 150ns. The signal from the test scintillator is delayed by an amount of 85ns to be able to remain inside the gate. Then it is digitised using charge-sensitive ADC (mentioned earlier). The data is stored in the PC using GPIB interface unit of CAMAC and is analysed off-line though it can be monitored on-line. The analysed results are presented in latter section. In order to gain in time, we have studied two scintillators at a time keeping those in between the trigger paddles as shown in figure-1.

We have tested basically five scintillators of different materials supplied by two different companies Bicron (referred as BC-408) and Kuraray; with various coupling of perspex light guide and WLS fibre. All the scintillators are of same dimension: 30 x 30 x 1 cm³. The WLS fibres are double-cladded Kuraray materials of diameter 0.83mm with emission spectrum in green region. They are embedded in the grooves on the top surface of the scintillator. The grooves are of rectangular cross-section made with CNC machine in the workshop.

In each case, the scintilator plate and light guide/fibre system has been wrapped first with a very good reflecting paper called Tyvek & then with special type of black paper called Tedlar to avoid light leakage. White reflecting paint (supplied by Bicron) has been
applied to the side surfaces of the plate after being polished. Whenever fibre is used, its open end has been allowed to pass through the perspex cookie using optical glue and the corresponding perpex face (along with fibre end) has been diamond polished. It is held firmly to the PMT face using spring under tension. Also the PMT used in this case has spectral response extended to green region (EMI-9954B) to optimally match to the emission spectrum of WLS fibre. Few strips of Aluminium sticking tape are put along the length of the fibres to fix them firmly inside the groove.

Figure 2: Schematic diagram of Parallel groove and $1\sigma$ groove layout

In first set of measurement we have studied how net light collection depends upon the geometry of the WLS fibre lay-out. For that, BC-408 PWLS groove layout is compared with BC-408 $1\sigma$ groove layout. In case of PWLS, four WLS fibres of varying length are put parallel to one another while in latter case a single fibre is embedded into a sigma-groove (figure-2). The length of the total amount of fibre embedded inside groove is almost same for both the scintillators. The farthest end of the fibres away from the PMT is mirrored to minimise the light escape from that end. Two sets of readings are taken by operating the sample scintillators at two different voltages of 1900V and 2000V. The data has been analysed and the result is presented in table-1. Pulse height spectra of the two layout obtained at 1900V are presented in figure-3.

After studying various layout of WLS fibre for same material (Bicron), a series of studies has been carried out on different materials of scintillator with same type of coupling. As the first sub-set in this series, we have taken $1\sigma$-WLS fibre coupling both for BC-408 and Kuraray. The fibre used here does not have mirrored end instead a strip of aluminium sticking tape has been put. All other procedures are same as above (PWLS vs $1\sigma$ case). The results are presented in (table-2). Second sub-set of this scheme includes the comparative study of BC-408 and Kuraray coupled with light guides. In this coupling the light guide is sandwiched between the scintillating tiles and the normal PMT (EMI-9807B) using optical glue. The shape of the light guide is trapezoidal with wider end facing the tile and narrower end to the PMT (fig-4). The sides of the light guide facing
Figure 3: Comparison of pulse height spectrum of BC-408 PWLS and 1σ-layout at 1900V to air are painted with the reflecting paint along with that of the scintillator. The sample scintillators are operated at 1400V and 1500V. The results are given in table-3 and a comparative account of the pulse height spectra of both the scintillator is given in figure-5.

Figure 4: Schematic diagram of Direct coupled scintillator

Methods to determine the average number of photo-electrons

The number of photo-electron emitted from the photo-cathode is the figure of merit of the scintillator under test. Because it is the direct signature of the fact that what fraction of the incident particle's energy gets converted into scintillated light. Precisely speaking; a scintillator is said to be more efficient if the number of photo-electron produced is proportionally large. Here four methods are attempted to evaluate it.

(1) Assuming the number of PE obeys Poisson statistics, the inefficiency of the scintillator which is equivalent to the probability of observing no photo-electron in the triggered
event can be found out as follows:
\[
\text{Inefficiency} = P_r(\lambda) \mid \lambda = 0 = \left\{ \frac{(n_{\text{poiss}})^k \exp(-n_{\text{poiss}})}{k!} \right\} \mid \lambda = 0 \\
\implies \text{Inefficiency} = \exp(-n_{\text{poiss}}) \\
\implies n_{\text{poiss}} = -\ln(\text{Inefficiency})
\]

where \( n_{\text{poiss}} \) is the average number of photo-electron emitted from the photocathode when a large number of events are recorded.

\( \lambda \) is the no. of photo-electron emitted in a particular event.

This Inefficiency is found out by taking the ratio of the no. of events registered in pedestal (measure of inefficiency of the detector) to the total number of events assuming that there is no other contribution in the pedestal. This method is best suited for small number of photo-electron where the pedestal contribution is substantial.

(II) As we know for large number of events, Poisson distribution tends to Gaussian distribution, it would be quite logical to use Gaussian approximation to the pulse height distribution for large number of PE. If \( \mu' \) is pedestal subtracted mean i.e. \( \mu' = (\mu - P) \) and \( \sigma \) the r.m.s. standard deviation of the pulse height distribution, then
\[
\frac{\sigma}{\mu'} = \frac{1}{\sqrt{n_{\text{gauss}}}} \quad \implies n_{\text{gauss}} = (\frac{\sigma}{\mu'})^2
\]

Typically the pulse height spectrum obtained in response to the passage of cosmic muon through the scintillator follows Landau distribution [fig-6] which is asymmetric towards high energy tail. So while fitting the Gaussian function around peak of the spectrum to find out most probable value (MPV) we have taken an asymmetric range. We have considered more channels below the peak compared to the the number of channels above it [fig-7]. MPV is in fact same as \( \mu' \).

(III) When the average number of PE is small enough so that the PMT can resolve the
Figure 6: Landau fit to the pulse height distribution obtained from Kuraray DC scintillator at 1400V

Figure 7: Gaussian fit to the peak portion of the same spectrum given in [fig-6]
respective photo-peaks due to one, two electrons etc then we can use Multi-peak method. In this method, the pulse height distribution (pedestal subtracted) is fitted to following function:

\[ h(x) = (\text{constant}) \sum_k (n_{\text{multi}})^k \exp\left(-\frac{n_{\text{multi}}}{k!}\right) \exp\left\{ -\frac{(x-ak-b)^2}{2k\sigma_1^2} \right\} \left(\sqrt{2\pi k\sigma_1}\right)^{-1} \]

with \( a \) is the channel interval between pedestal and 1st photo-peak

\( b \) is the position of the pedestal peak

\( \sigma_1 \) is r.m.s. standard deviation of pulse height distribution for single PE

\( n_{\text{multi}} \) is average number of PE from Multi-peak method

In the process of taking measurement with various scintillators we have obtained a spectrum where we can use this Multi-peak method. It is presented in figure-10 along with the measured value of PE.

(IV) In the last method; we have found out ADC channel per PE. This method is termed as Calibration method. In order to get ADC channel per PE, the intensity of scintillated light has to be attenuated by putting some mask in between the cookie and the PMT such that less amount of light would reach the photo-cathode. In our case a series of white paper cut into circular shape has been chosen as mask (fig.-8). We have kept on increasing the number of mask in front of the PMT and analysed the data obtained. This iterative method is continued up-to a level where the mask is just sufficient to yield

![Figure 8: Experimental setup for attenuation measurement](image)

average number of PE about one or less than that. The resultant pulse height spectrum has a single peak along with a huge pedestal (figure-9). The inefficiency is so large that the peak of the spectrum corresponds to single PE event. Thus the ADC channel per PE (\( \delta \)) is found out by fitting the peak region. Having known \( \delta \) average number of PE can be found out for any spectrum obtained from any scintillator using the same PMT and same applied voltage. The pedestal corrected value of the spectrum is measured first which is to be divided by \( \delta \) to get required result. We have taken a series of data for two different scintillators with high voltages 1900V and 2000V to find out \( \delta \) for the given PMT at given voltage. The corresponding results are given in table-4.
Figure 9: Typical spectra obtained from BC-408 1σ layout after masking the scintillated light at 1900v
Results

Dependence of NPE on the geometry of the WLS fibre lay-out

<table>
<thead>
<tr>
<th>Scintillator specification</th>
<th>Voltage applied</th>
<th>Pedestal P</th>
<th>Gaussian fit $\mu$</th>
<th>Gaussian fit $\sigma$</th>
<th>MPV $(\mu-P)$</th>
<th>MPV NPE</th>
<th>$\delta$</th>
<th>NPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWLS fibre layout (4 fibres)</td>
<td>1900</td>
<td>13.32</td>
<td>120.7</td>
<td>33.74</td>
<td>107.4</td>
<td>10.13</td>
<td>4.632</td>
<td>23.18</td>
</tr>
<tr>
<td>1σ-fibre layout</td>
<td>2000</td>
<td>13.88</td>
<td>215.31</td>
<td>61.57</td>
<td>201.43</td>
<td>10.7</td>
<td>9.596</td>
<td>20.99</td>
</tr>
</tbody>
</table>

From table-1, we find that the PE yield for PWLS configuration is more compared to 1σ-layout though the length of the total fibre inside the groove is same for both. The reason is the scintillated light collected by the fibre while moving to the end of the scintillator tile undergoes more attenuation in case of 1σ-layout.

If $I_{00}$ is the total light collected by the fibre inside tile, the amount of light that will reach at the PMT level $I_0$ is given by the following expression:

$$I_0 = \left(\frac{d_2}{L}\right) \left(1 - \exp\left(-\frac{d}{\lambda}\right)\right) \exp\left(-\frac{d}{\lambda}\right)$$

with $L$ is length of the fibre inside the tile through which light is collected as well as attenuated in due course of collection and $d$ is length outside the tile which only attenuates the light passing through. $\lambda$ is the attenuation length of the fibre ($\approx 2$ m). Since the light collected by the fibre is proportional to its length with area of cross-section fixed; $I_{00}$ would be same both for PWLS and 1σ-layout. Then incorporating overall attenuation of the collected light inside the fibre; the ratio of the light collected at PMT photo-cathode level would be

$$\left(\frac{I^*}{I_0}\right) = \frac{\left(1 - \exp\left(-\frac{d}{\lambda}\right)\right) \exp\left(-\frac{d}{\lambda}\right)}{4 \left(1 - \exp\left(-\frac{d_2}{\lambda}\right)\right) \exp\left(-\frac{d_2}{\lambda}\right)}$$

In the above expression factor-4 indicates the presence of four fibres in PWLS layout and $d_2$ is the average length of those fibres outside the tile i.e. in between the scintillator edge and the cookie. Putting all the values in above expression, it is found that $\left(\frac{I^*}{I_0}\right) = 0.95$ i.e. 1σ-layout is calculated to be 5% less efficient than PWLS layout whereas the ratio of PE for both the case is measured to be 0.79. The difference in geometrical design of grooves for two scintillators is the major reason lying behind the poor matching of two values.

Dependence of NPE on different materials of the scintillating tiles

From results given in table-2; it is well established the light collection efficiency of the direct coupled scintillator is much more than that of WLS fibre lay-out. But the former introduces unusable dead-space in the whole detector system. In both the case of BC-408 and Kuraray DC scintillator; the dead-space constitute 29.5% of the available scintillator volume. In direct contrast to it, WLS fibre lay-out practically introduces no dead space.

Taking the material of the scintillator into account, BC-408 (supplied by BICRON) has been found to be more efficient than that supplied by KURARAY. This can be further
Table 2: Number of PE obtained from BC-408 DC and Kuraray DC scintillators

<table>
<thead>
<tr>
<th>Scintillator specification</th>
<th>PMT used</th>
<th>High volt applied</th>
<th>Pedestal P</th>
<th>Gaussian fit</th>
<th>MPV (µ-P)</th>
<th>NPE (Gauss.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC-408 Direct Scintillator</td>
<td>Blue</td>
<td>1400</td>
<td>9.64</td>
<td>140.86</td>
<td>20.88</td>
<td>131.22</td>
</tr>
<tr>
<td></td>
<td>PMT</td>
<td>1500</td>
<td>10.13</td>
<td>274.57</td>
<td>40.95</td>
<td>264.44</td>
</tr>
<tr>
<td>Kuraray Direct Scintillator</td>
<td>Blue</td>
<td>1400</td>
<td>12.5</td>
<td>103.6</td>
<td>15.43</td>
<td>91.1</td>
</tr>
<tr>
<td></td>
<td>PMT</td>
<td>1500</td>
<td>13.58</td>
<td>189.24</td>
<td>28.37</td>
<td>175.66</td>
</tr>
</tbody>
</table>

confirmed from the following results (table-3) obtained from 1σ WLS fibre coupling both of BC-408 and Kuraray.

Table 3: Number of PE obtained from BC-408 and Kuraray 1σ-WLS fibre lay-out

<table>
<thead>
<tr>
<th>Scintillator specification</th>
<th>Voltage applied</th>
<th>Pedestal P</th>
<th>Gaussian fit</th>
<th>MPV (µ-P)</th>
<th>(Gauss.) NPE</th>
<th>(calibrat.) NPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC-408 1σ-Layout</td>
<td>1900</td>
<td>8.75</td>
<td>69.28</td>
<td>27.88</td>
<td>60.53</td>
<td>4.71</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>8.75</td>
<td>140.02</td>
<td>61.32</td>
<td>131.27</td>
<td>4.58</td>
</tr>
<tr>
<td>Kuraray 1σ-Layout</td>
<td>1900</td>
<td>13.25</td>
<td>73.34</td>
<td>41.36</td>
<td>60.09</td>
<td>2.11</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>13.62</td>
<td>157.84</td>
<td>94.62</td>
<td>144.22</td>
<td>2.32</td>
</tr>
</tbody>
</table>

Effect of attenuation on number of photo-electron (NPE)

Table 4: No of PE obtained from BC-408 Parallel and 1σ-WLS fibre lay-out after attenuation, by putting four masks

<table>
<thead>
<tr>
<th>Scintillator specification</th>
<th>High volt. voltage</th>
<th>Pedestal P</th>
<th>Mean (µ) Gaussian fit</th>
<th>MPV (µ-P);δ</th>
<th>Average NPE (Poisson)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWLS-fibre layout (PMT#1);mask</td>
<td>1900</td>
<td>13.398</td>
<td>18.03</td>
<td>4.632</td>
<td>0.5779</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>13.398</td>
<td>22.994</td>
<td>9.596</td>
<td>0.43954</td>
</tr>
<tr>
<td>1σ-fibre layout (PMT#2);mask</td>
<td>1900</td>
<td>8.0</td>
<td>14.71</td>
<td>6.71</td>
<td>0.2864</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>8.0</td>
<td>21.05</td>
<td>13.05</td>
<td>0.3062</td>
</tr>
</tbody>
</table>

Comparing above result with the result we have got earlier for PWLS and 1σ layout (table-1); it is quite apparent that on attenuating the scintillated light collected through the WLS fibre the average number of photo-electron reduces by a fraction of 0.02 or even less. Also the inefficiency becomes so large (typically 67.2% of the total event registered) that one can say the spectrum is due to a single photo-electron. A typical spectrum due to one photo-electron has been shown earlier (figure-9). Then the corresponding MPV found out by fitting the rising edge of the peak represents ADC channel per PE. These values are basic ingredients of Calibration method used to evaluate the average number of PE. The ADC channel per PE as given in table-4 depends on the voltage applied to the PMT (for same PMT). Also it varies for different PMT.

As it is explained in earlier section when the average number of PE is small; one, two and three photo-electron peaks can be clearly seen as shown in the figure-10. Then we can use Multi-peak methods to evaluate the number of photo-electron. The result obtained
Figure 10: Typical pulse height spectrum obtained with EMI-9954B PMT. Zero, one and two photo-electron peaks are clearly seen. The spectrum is fitted with the function $h(x)$ by using this method is quite comparable to the result of Inefficiency method (which is the best method for small number of PE). That can be made more accurate by increasing the 1st dynode gain of the PMT.

**Error analysis**

In order to study the reliability of the results presented here, we have repeated several sets of experiments under similar conditions to find out systematic error. It is found that the peak position of the pulse height spectra differed by 5–10%. Accordingly the number of PE is changed by 10–12%. This could be due to mis-alignment of the trigger paddles, gain fluctuation of of the PMT, wrong positioning of the PMT w.r.t. the tile etc.

The values of fitted parameters also inherit some statistical errors. For example, the statistical errors associated with $\mu$ and $\sigma$ of the Gaussian fittings done so far are typically 0.2% and 5% of the fitted value. Then the statistical errors associated with the number of photo-electron have been computed to be 5% of the measured values.

**Summary**

From our series of studies, we have found out the light collection efficiency of BC-408 is better than that of Kuraray scintillator. The WLS fibre readout system is found to be more efficient than optical light guide having taken the unusable dead-space inherited with the light guide into account. In the two varieties of fibre readout system studied, the light yield in case of fibres embedded on parallel grooves is found to be more compared to that of 1σ grooves. But in practice handling four fibres outside the tile with the other ends glued to the cookie is more inconvenient.

Comparing the results of different methods to determine average number of PE, we have found the Calibration method to be the best one. Poisson and Gaussian methods are suitable only on two opposite extremes: 1st one for small number of PE while 2nd one for large number. One can also use Multi-peak method, if the PMT is sensitive enough to resolve the respective peaks for one, two photo-electrons. The calibration method requires
the same PMT to be operated at the same voltages. Also it is found that within error limit the number of PE remains independent of the applied voltages. Only the spectrum gets shifted in ADC channel due to increase of inter-dynode gain.

Acknowledgement

It is a pleasure on my part to acknowledge the guidance of Dr. K. Mazumdar throughout my project. I thankfully acknowledge the fruitful discussion with Drs. K. Sudhakar and G. Majumder on various aspect of the reported topic. Finally I would like to mention that a few part of this work has been done along with my colleague Md. Azizur Rahaman but the data is analysed independently.

References


