Testbeam analysis for a scintillating fibre telescope

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Abstract

A scintillating fibre (SciFi) telescope is constructed using the same technology as the LHCb SciFi Tracker. The results of the telescope testbeam measurements performed at SPS at CERN in November of 2015 are given in this document. The distributions of cluster number, size, position and sum of the number of fired pixels at different over-voltages are shown. With the over-voltage at 3.5 V, the track resolution at the central plane is determined to be 17\,\mu m and the single plane resolution is around 33\,\mu m. The hit detection efficiencies are around 99\% for all planes.
1 Introduction

During the LHCb upgrade period, the current Inner Tracker and Outer Tracker, using silicon strip sensors and straw-tubes respectively [1], will be replaced by a single technology detector, the scintillating fibre (SciFi) Tracker [2,3]. The scintillating fibre telescope is based on the same technology as the LHCb SciFi Tracker. It is used as a particle tracker at testbeam in order to measure the track resolution and detection efficiency. The study of the telescope can also help to better understand the performance of the LHCb SciFi Tracker.

The scheme of the telescope is shown in Fig. 1. The coordinate system indicated is used throughout this document. It consists of 5 detection stations each composed of X and Y planes. The fibre mats are 10 cm long. A SiPM photodetector is used for the readout of each plane, and each SiPM consists of two silicon dies with 64 channels [4]. A mirror is added at the end of each fibre mat to increase light yield. The fibre mats have either 5 or 6 layers, as listed in Table 1. The readout of SiPMs is done with VATA64 electronics, and the interface to the computer is done with USB Board. The Uplink IDs for all the planes are also listed in Table 1.

![Figure 1: Schematics of the telescope.](image)
Table 1: General information of the telescope.

<table>
<thead>
<tr>
<th>Station</th>
<th>Uplink X</th>
<th>Uplink Y</th>
<th>#layer X</th>
<th>#layer Y</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>100/101</td>
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<td>120/121</td>
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<td>5</td>
<td>150/151</td>
<td>152/153</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

2 Measurements

During the testbeam, measurements were performed with SiPMs at different over-voltages ($\Delta V$). Calibration scans are also taken with no bias applied to the SiPM (pedestal) and with LED injection for the ADC gain calculation. In a second time, measurements on station 3 were performed in the lab with an electron gun [5].

3 Clustering

Channels with signals are grouped together into clusters, which are used to determine the crossing point of the particle. To find clusters, we need first to convert the amplitude from ADC value to the number of fired pixels. The distributions of the ADC value for one channel of Y3 plane with LED and beam injection are shown in Fig. 2 for testbeam and electron scan respectively. The USB Boards can output ADC values only up to 4095, leading to the electronic saturation. The number of incident photons is not equal to the number of fired pixels because of SiPM pixel saturation. If two photons enter the same pixel only one photon is detected. What is measured directly from the ADC output is the number of fired pixels, which is calculated as

$$N(\text{fired pixels}) = \frac{\text{ADC value} - \text{ADC pedestal}}{\text{ADC gain}}.$$  \hspace{1cm} (1)

To account for the pixel saturation, the light yield, i.e. number of photon-electrons is determined using

$$N(\text{p.e.}) = \log[1 - \frac{N(\text{fired pixels})}{N(\text{pixels in one channel})}]/\log[1 - \frac{1}{N(\text{pixels in one channel})}].$$  \hspace{1cm} (2)

The ADC pedestal stands for the ADC value when there is no input at all, which manifests itself as the shift of the first ADC peak from zero and can be clearly seen in the ADC distributions as displayed in Fig. 2. It corresponds to the electronic offset, which is calibrated using the pedestal runs. The ADC gain for each channel is determined using the LED dataset since its ADC distribution has a much clearer peak structure. The ADC gain is basically the distance between the peaks and is calculated in practice with a Fourier Transform. To account for the discrepancy between the ADC gain of LED and data runs, a correction factor is introduced as the ratio of the ADC gain of the data run to the LED run calculated with all channels. The comparisons of the ADC gain of X3 and
Figure 2: ADC value distributions for one channel of Y3 plane with both LED (left) and beam (right) injection at testbeam (top) and electron scan (bottom) respectively.

Figure 3: Comparisons of the ADC gain of X3 and Y3 plane at different over-voltages for both testbeam (left) and electron scan (right). Since the temperature changes the break down voltage by 54 mV/K, a small shift between the testbeam and electron scan is expected.

The next step is to construct cluster with signal in all channels. The clusters are constructed every 64 channels for each silicon die of the SiPMs. Three thresholds, a) seed threshold, b) neighbour threshold and c) sum threshold, are used for the cluster determination. If one channel has a number of fired pixels larger than the seed threshold, it will be taken as the seed of a cluster. Then if the number of fired pixels of the neighbour channel is larger than the neighbour threshold, this channel will be added to the cluster and the comparison will continue with the channel next to it. The search will stop when the number of fired pixels of the channel considered falls below the neighbour threshold.
Finally, the cluster will be accepted only if the sum of the number of pixels of all the channels included in the cluster is larger than the sum threshold. The clusters of one testbeam event is shown in Fig. 4 as an example.

![Event Display](image)

Figure 4: Clusters of one testbeam event for X planes (top) and Y planes (bottom) respectively. The y axis indicates the light yield.

## 4 Cluster properties

The number, size, position and light yield ($N(\text{p.e.})$) of the clusters are analysed and compared between the testbeam and the electron scan in this section. To simplify the presentation, all the figures are given at $\Delta V = 3.5\, V$ as an example.

### 4.1 Number of clusters per event

The distributions of the number of clusters in one event for each plane are displayed in Fig. 5 for testbeam and electron scan respectively. For the electron scan, the number of events with no clusters are very large due to the scan procedure. The distributions all indicate that the most of the events with clusters have only one cluster in each plane. To make a more clear comparison between the testbeam and electron scan, the normalised cluster number distributions of Y3 for testbeam and electron scan in the region of cluster number $> 1$ are drawn together in Fig. 6. The cluster number of testbeam is generally larger compared to the electron scan. The trigger of particle is only accepted if no particle...
was present during the last 5 µs, thus the comparison indicates that there are more secondaries in the testbeam.

![Distribution of cluster number for testbeam and electron scan](image)

Figure 5: Distributions of cluster number for each plane for testbeam (top) and electron scan (bottom) respectively.

### 4.2 Cluster size

The distributions of number of channels in one cluster for each plane are shown in Fig. 7 for testbeam and electron scan respectively. Regarding the testbeam data, the cluster size of X3 is clearly larger than the other planes. This issue was checked and found out to be due to an imperfect gluing of the mirror at the end of the fibre mat. To make a more clear comparison between the testbeam and electron scan, the normalised cluster size distributions of Y3 for testbeam and electron scan are drawn together in Fig. 8. The electron clusters tend to have a larger size, which means electrons deposit energy in more channels. The electrons are at low energy (1 MeV) and undergo multiple scattering in the fibre mats, spreading signal on a wide region.
4.3 Cluster position

The cluster position is defined as

$$\frac{\sum_{i=1}^{n}(N_i(p.e.) \times \text{channel number}_i)}{\sum_{i=1}^{n} N_i(p.e.)}$$  \hspace{1cm} (3)$$

where $n$ stands for the number of channels of the cluster, $N_i(p.e.)$ is the number of photon-electrons of the $i$th channel in the cluster, and channel number$_i$ is the channel number of the $i$th channel. The distributions of cluster position for each plane are displayed in Fig. 9 for testbeam and electron scan respectively. The cluster position distribution is a direct monitoring of the beam profile. For the test beam, the peak widths for all the X (Y) planes are reasonably the same, which indicates the particles went in parallel with each other and there is no significant angular misalignment. A shift of around 20 channels is seen between X1 and X5 plane, while in the y direction the beam range is almost the same for all planes. It indicates that the vertical mechanical alignment is good however the horizontal alignment is much worse. For the electrons, as expected from the scan, clusters are homogenously spread. The peak in the middle comes from the gap between the two SiPM dies. A particle going through the gap will end up with one cluster at the channel on each side of the gap. So the numbers of clusters at the channels close to the gap are enhanced. The peaks on the left and right boarder are due to the edges of the SiPMs. The channel in the middle with zero clusters is a dead channel.

4.4 Light yield

The distributions of the sum of the number of fired pixels in one cluster for each plane are displayed in Fig. 10 for testbeam and electron scan respectively. The distributions of
Figure 7: Distributions of cluster size for each plane for testbeam (top) and electron scan (bottom) respectively. X3 mirror is not glued properly.

light yield, i.e. the sum of the number of photon-electrons in one cluster for each plane are displayed in Fig. 11 for testbeam and electron scan respectively. The small peak at the left end of the distributions comes from noise. The peak of X3 plane is significantly larger than the others because of the imperfect mirror gluing. For the testbeam, the distributions of planes with 6 layers (X1, Y1, Y3 and Y5) have clearly a superposition of two peaks in the central region, which is due to the staggered multi-layer fibre arrangement as confirmed by simulation. Particles crossing the mats at different positions will have different interaction lengths leading to different amount of scintillating photons produced. For mats with 5 layers, there is only one peak determined by the different geometry. For the electron scan, there is only one peak for Y3 because the electrons are not in parallel and the multiple scattering effect is larger. The light yields are also compared between
different $\Delta V$ for testbeam and electron scan respectively, as shown in Fig. 12. The light yield at one $\Delta V$ is taken as the most probable value of the corresponding distribution. The values are obtained from gaussian fits of the light yield distributions excluding the lower end peak. They are not accurately the numbers of photon-electrons released, especially for the 6-layer planes, but can somehow give hints on the dependence of light yield on over-voltage. From both testbeam and electron scan comparisons, it can be seen that the light yields of 6-layer planes are larger than those of the 5-layer planes, and the light yield increases with $\Delta V$. The light yield will saturate for $\Delta V$ higher than 3.5 V. It is mainly due to pixel and electronic saturation.

5 Track analysis

5.1 Alignment

During the testbeam setup, the mechanical alignment was completed to the level of 100 $\mu$m. An offline alignment of the tracking stations with respect to each other is needed in order to improve this and to provide best resolution tracks to other test modules. Only one alignment shift is allowed per measured point. The z position of the planes are taken to be fixed and the shifts of the X and Y planes in x or y direction respectively are calculated (coordinate system as shown in Fig. 1). Since this is an internal alignment, the external planes (X1, Y1, X5 and Y5) are fixed otherwise a random overall shift can be assigned. The alignment of angular rotation is not considered currently since:

(a) the beam region considered is very small thus the effect of angular misalignment is largely suppressed;
Figure 9: Distributions of cluster position for each plane for testbeam (top) and electron scan (bottom) respectively. The red areas indicate the central regions used for the alignment.

(b) the angles are well controlled by the mechanical alignment thus the angular misalignment is expected to be rather small.
Figure 10: Distributions of the number of fired pixels for each plane for testbeam (top) and electron scan (bottom) respectively. X3 mirror is not glued properly.

To further ensure this, the clusters used are restricted to the central region as shown in Fig. 9. X3 is excluded from tracking and alignment due to the bad mirror gluing.

To do the alignment, tracks need to be reconstructed first. Tracks are built from the clusters on each plane, which correspond to hits of particles. The cluster position defined in Eq. 3 is taken as the hit position. A track can be determined using four parameters as

\[
\begin{align*}
  x &= x_0 + l_x \times z \quad (a) \\
  y &= y_0 + l_y \times z \quad (b),
\end{align*}
\]

where \((x, y, z)\) stands for the coordinate of the track. Since \(x\) and \(y\) are independent of each other, \((a)\) and \((b)\) in Eq. 4 can be determined separately using the same method, which is explained in the following taking the track reconstruction in the \(y\) direction as
Figure 11: Distributions of light yield for each plane for testbeam (top) and electron scan (bottom) respectively. X3 mirror is not glued properly.

an example. Using each two hits which are not in the same plane, a set of $y_0$ and $l_y$ is calculated. Several sets of $y_0$ and $l_y$ can be obtained with all the hits. The obtained $(y_0, l_y)$ values are filled into a two dimensional histogram. The center value of the bin which has the most candidates is taken to be the preliminary value of $y_0$ and $l_y$. If the distance of a hit to the track determined by this set of $y_0$ and $l_y$ is larger than 0.5 mm, the hit is rejected. After the hit rejection, the number of clusters in one plane is checked and if there are more than one clusters found, the event will be rejected. Then a linear fit is performed to make a final check of the track quality. If the p-value of the fit is smaller than 0.1, the event will also be removed.

The alignment is performed with the hits remaining after all the selections. It is implemented using MILLEPEDE, a package capable of solving the linear least square
problem with a very large number of parameters and used for detector alignment. There are 9 planes to be aligned (X3 excluded) which results in 9 shift parameters. They are denoted as $S_{X(Y)1(2,3,4,5)}$ and represent the shift in x or y direction for the corresponding X or Y planes. The shift parameters can affect all the tracks thus are taken as global parameters. For each track, a set of local parameters are defined as in Eq. 4. The shifts should give a minimum difference between the measured and expected (obtained from
track fit) \( x \) or \( y \) values quantified as

\[
\sum_{\text{all tracks}} \left[ \sum_{i=1,2,4,5} \frac{(x_i(\text{observed}) - x_i(\text{expected}))^2}{\sigma^2_{X_i}} + \sum_{i=1,2,3,4,5} \frac{(y_i(\text{observed}) - y_i(\text{expected}))^2}{\sigma^2_{Y_i}} \right],
\]

(5)

where \( x_i/y_i(\text{observed/expected}) \) stands for the measured/expected \( x/y \) value of the hit in the corresponding plane, and \( \sigma_{X_i/Y_i} \) is the resolution of the corresponding plane. The resolutions of planes with 5 or 6 layers can be slightly different. For simplicity, they are assumed to be the same and thus will not affect the result when the resolution changes.

The measured \( x/y \) value is the hit position observed. The expected value is a function of the global and local parameters. Taking the hit in Y3 plane as an example, it is

\[
y_3(\text{expected}) = S_{Y3} + y_0 + l_y \times z_3, \tag{6}
\]

where \( z_3 \) is the \( z \) position of the Y3 plane. The shift parameters are determined using all the data runs with different \( \Delta V \) separately as listed in Table 2. They show a good consistency between each other. They also indicate that the nominal and aligned positions are matching as good as 100 \( \mu \)m.

Table 2: Summary of the global shifts.

<table>
<thead>
<tr>
<th></th>
<th>( \Delta V = 2.5 ) V</th>
<th>( \Delta V = 3.0 ) V</th>
<th>( \Delta V = 3.5 ) V</th>
<th>( \Delta V = 4.0 ) V</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_{X1}/\mu m )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( S_{X2}/\mu m )</td>
<td>54</td>
<td>52</td>
<td>52</td>
<td>51</td>
</tr>
<tr>
<td>( S_{X3}/\mu m )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( S_{X4}/\mu m )</td>
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<td>17</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>( S_{X5}/\mu m )</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( S_{Y2}/\mu m )</td>
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<td>93</td>
<td>93</td>
<td>93</td>
</tr>
<tr>
<td>( S_{Y3}/\mu m )</td>
<td>-33</td>
<td>-34</td>
<td>-34</td>
<td>-34</td>
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<tr>
<td>( S_{Y4}/\mu m )</td>
<td>34</td>
<td>33</td>
<td>34</td>
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</tr>
<tr>
<td>( S_{Y5}/\mu m )</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

5.2 Track resolution

After the internal alignment, tracks can be reconstructed using the same strategy as described in Sec. 5.1. The plane whose resolution is measured is excluded from track reconstruction in order to avoid any bias. The residual is defined as the difference between the measured hit position and the reconstructed track crossing position. The residual of each plane can be decomposed into two contributions, the track resolution and the proper resolution as

\[
R^2 = \sigma_T^2 + \sigma_P^2, \tag{7}
\]

where \( R \) is residual, \( \sigma_T \) is the track resolution, and \( \sigma_P \) is the proper resolution. This relation is due to that the distance between the measured hit and reconstructed track can be interpreted as the distance between the measured hit and the real track plus
the distance between the real track and the reconstructed track. For each plane, $R$ is determined by the fit to the residual distribution using a central Gaussian with power tails and taken as the sigma of the Gaussian part, as shown in Fig. 13 for all Y planes with $\Delta V = 3.5 \text{V}$. The residual distributions are all centred around 0, which proves that the shift in the corresponding direction has been successfully corrected by the alignment. Table 3 lists the $R$ values for all data runs. The $R$ values are symmetric with respect to the central plane with a minimum value in the middle plane as expected because $\sigma_T$ is minimum at this position. For $\Delta V = 2.5 \text{V}, 3.0 \text{V}$ and $3.5 \text{V}$, the residuals are almost the same. It suggests that the increase of $\Delta V$ will not improve the resolution. For $\Delta V = 4.0 \text{V}$ the resolution becomes worse, which can be due to electronics saturation. The contributions from track resolution and hit resolution need to be disentangled. For the central plane (Y3), we have

$$\sigma_T = \alpha \times \sigma_P, \quad (8)$$

where $\alpha$ is a coefficient which can be determined using a simulation. The $\sigma_P$ of each plane are assumed to be the same in the simulation. Together with Eq. 7 and the $R$ value, $\sigma_P$ and $\sigma_T$ can both be determined for Y3. With the $\sigma_P$ and $R$ given, the $\sigma_T$ of all the other planes can also be calculated. The $R$, $\sigma_T$ and $\sigma_P$ for all the Y planes with $\Delta V = 3.5 \text{V}$ are listed in Table 4.

Table 3: Summary of the residuals of all Y planes for all data runs.

<table>
<thead>
<tr>
<th>Y Plane</th>
<th>$\Delta V = 2.5 \text{V}$</th>
<th>$\Delta V = 3.0 \text{V}$</th>
<th>$\Delta V = 3.5 \text{V}$</th>
<th>$\Delta V = 4.0 \text{V}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{Y1}/\mu\text{m}$</td>
<td>50</td>
<td>48</td>
<td>51</td>
<td>53</td>
</tr>
<tr>
<td>$R_{Y2}/\mu\text{m}$</td>
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<tr>
<td>$R_{Y3}/\mu\text{m}$</td>
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<td>$R_{Y4}/\mu\text{m}$</td>
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<td>39</td>
<td>40</td>
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<tr>
<td>$R_{Y5}/\mu\text{m}$</td>
<td>50</td>
<td>50</td>
<td>51</td>
<td>53</td>
</tr>
</tbody>
</table>

Table 4: Summary of the $R$, $\sigma_T$ and $\sigma_P$ for all the Y planes with $\Delta V = 3.5 \text{V}$.

<table>
<thead>
<tr>
<th>Y Plane</th>
<th>$R/\mu\text{m}$</th>
<th>$\sigma_P/\mu\text{m}$</th>
<th>$\sigma_T/\mu\text{m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y1</td>
<td>51</td>
<td>33</td>
<td>39</td>
</tr>
<tr>
<td>Y2</td>
<td>41</td>
<td>33</td>
<td>24</td>
</tr>
<tr>
<td>Y3</td>
<td>37</td>
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</tr>
<tr>
<td>Y4</td>
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</tr>
<tr>
<td>Y5</td>
<td>51</td>
<td>33</td>
<td>39</td>
</tr>
</tbody>
</table>

6 Hit detection efficiency

The hit detection efficiencies for the Y planes are also determined. Considering one plane, first tracks are reconstructed using hits from other planes. Then the hits in this plane
are compared to the reconstructed track. If there is one hit with a distance to the track smaller than ±0.4 mm (value determined according to Fig. 13), it is considered as an efficient hit. The hit efficiencies for all the Y planes with different over-voltages are listed in Table 5. They are generally at the level of 99%, which is below our expectation, and further investigation is needed! The efficiencies are similar for all planes, and only change slightly with respect to different ∆V.

7 Summary

As a summary, with the data collected with the scintillating fibre telescope during the 2015 November testbeam, the cluster number, size, position and light yield at different ∆V were analysed and compared with the results of the electron scan measurements performed in the lab. A one dimensional alignment procedure is implemented with the MILLEPEDE package. The track resolution of the central plane can reach a precision of 17 µm. The hit resolution of the fibre mats is determined to be 33 µm for ∆V = 3.5 V. The hit detection
Table 5: Summary of hit efficiencies rejecting all hits outside ±400 µm for the Y planes with different over-voltages.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta V = 2.5 V$</th>
<th>$\Delta V = 3.0 V$</th>
<th>$\Delta V = 3.5 V$</th>
<th>$\Delta V = 4.0 V$</th>
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</thead>
<tbody>
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<td>Y1 Hit efficiency/%</td>
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<td>98.8</td>
<td>98.8</td>
<td>98.8</td>
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<tr>
<td>Y2 Hit efficiency/%</td>
<td>98.6</td>
<td>98.7</td>
<td>98.7</td>
<td>98.7</td>
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<tr>
<td>Y3 Hit efficiency/%</td>
<td>98.6</td>
<td>98.7</td>
<td>98.7</td>
<td>98.7</td>
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<tr>
<td>Y4 Hit efficiency/%</td>
<td>98.7</td>
<td>98.7</td>
<td>98.8</td>
<td>98.7</td>
</tr>
<tr>
<td>Y5 Hit efficiency/%</td>
<td>98.8</td>
<td>98.8</td>
<td>98.9</td>
<td>98.8</td>
</tr>
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</table>

...efficiencies for all planes are around 99%.

References


