Performance Study of Pair-monitor
(for ILD)

Yutaro Sato
Tohoku Univ.
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Pair-monitor

Pair-monitor is a silicon pixel detector to measure the beam profile at IP.

- The distribution of the pair B.G. is used.
  - The same charges with respect to the oncoming beam are scattered with large angle.
  - The scattered particles have information on beam shape.
- The pair-monitor is required to measure the beam size with 10% accuracy.
We have developed
- performance study of the pair-monitor.
- development of the readout ASIC for the pair-monitor.

Contents

• The combined analysis with BeamCal was performed.
  - Pair-monitor: silicon pixel detector to measure hit counts
  - BeamCal: calorimeter to measure energy deposit
• Beam parameters ($\sigma_x$, $\sigma_y$, $\Delta_y$) were reconstructed using the Taylor matrix method (second order).

\[ \Delta_y = \delta_y / \sigma_y \]
Simulation setup

- CM energy : 500GeV
- Nominal beam size \((\sigma_x^0, \sigma_y^0, \sigma_z^0) = (639\text{nm}, 5.7\text{nm}, 300\ \mu \text{m})\)
- Tools : CAIN (Pair background generator) 
  Jupiter (Tracking emulator)
- Magnetic field : 3.5 T + anti-DID
- Pair-monitor is located in front of the BeamCal.
- Scattered e\(^+\) was studied.

![Diagram of simulation setup](image-url)
Matrix method for reconstruction

The measurement variables are used for the reconstruction.

The measurement variables can be expanded by the Taylor expansion.

Measurement variable \((M)\)  

Beam parameter \((X)\)

\[
\begin{pmatrix}
m_1 \\
\vdots \\
m_n 
\end{pmatrix} = \mathbf{A} \begin{pmatrix}
\sigma_x \\
\sigma_y \\
\Delta_y 
\end{pmatrix} + \begin{pmatrix}
\sigma_x \\
\sigma_y \\
\Delta_y 
\end{pmatrix} \mathbf{B} \begin{pmatrix}
\sigma_x \\
\sigma_y \\
\Delta_y 
\end{pmatrix} + \cdots
\]

\[
= \mathbf{A} \mathbf{X} + \mathbf{X}^T \mathbf{B} \mathbf{X} + \cdots
\]

\[\mathbf{A} = \begin{pmatrix}
\frac{\partial m_1}{\partial \sigma_x} & \frac{\partial m_1}{\partial \sigma_y} & \frac{\partial m_1}{\partial \Delta_y} \\
\frac{\partial m_2}{\partial \sigma_x} & \frac{\partial m_2}{\partial \sigma_y} & \frac{\partial m_2}{\partial \Delta_y} \\
\vdots & \vdots & \vdots 
\end{pmatrix}
\]

The beam parameters are reconstructed by the inverse matrix.

\[
\mathbf{X} \equiv \begin{pmatrix}
\sigma_x \\
\sigma_y \\
\Delta_y 
\end{pmatrix} = [\mathbf{A} + \mathbf{X}^T \mathbf{B} + \cdots]^{-1} \mathbf{M}
\]
Measurement variables

8 measurement variables were defined.

<table>
<thead>
<tr>
<th>Pair-monitor</th>
<th>BeamCal</th>
</tr>
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<tbody>
<tr>
<td>$R_{\text{max}}$</td>
<td>$R_{\text{ave}}$</td>
</tr>
<tr>
<td>$N_{\text{D1}}/N_{\text{all}}$</td>
<td>$N_{\text{D}}/N_{\text{all}}$</td>
</tr>
<tr>
<td>$N_{\text{U}}/N_{\text{D2}}$</td>
<td>$N_{\text{U}}/N_{\text{D}}$</td>
</tr>
<tr>
<td>$1/N_{\text{all}}$</td>
<td>$1/E_{\text{dep}}_{\text{all}}$</td>
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- **Spread**
- Ratio of the particular region
- Total hit or energy deposition

We introduce above measurement variables.
Spread of pair B.G. distribution

The spread of the pair B.G. distribution changes, according to the transverse momentum of the pairs.

\[ \sigma_x = 639 \text{ [nm]} \]
\[ \sigma_x = 958.5 \text{ [nm]} \]

Pt distribution at IP

Measurement variables were defined.

\[ R_{\text{max}} : \text{Radius to contain 97.5\% of all the hits. (Pair-monitor)} \]
\[ R_{\text{ave}} : \text{Average radius weighted by energy deposit. (BeamCal)} \]

\[ R_{\text{ave}} = \frac{\sum R_i \times E_{\text{dep}_i}}{\sum E_{\text{dep}_i}} \quad (R_i \text{ is the radius of the i-th cell}) \]
Variable: $R_{\text{max}}$ and $R_{\text{ave}}$

$R_{\text{max}}$ and $R_{\text{ave}}$ were obtained with various beam parameters.

$R_{\text{max}}$ [cm] v.s. Horizontal beam size ($\sigma_x$) [nm]

$R_{\text{ave}}$ [cm] v.s. Horizontal beam size ($\sigma_x$) [nm]

$\sigma_y = 5.7$ [nm]

$\sigma_y = 8.55$ [nm]

$\sigma_y = 11.4$ [nm]

$\sigma_y = 17.1$ [nm]

$R_{\text{max}}$ and $R_{\text{ave}}$ decrease for larger horizontal beam size ($\sigma_x$).
Scattered direction at IP changes with the beam parameters.

**φ distribution at IP**

The measurement variables were defined from the pair-monitor.

- \( N_{D1} / N_{all} \) for vertical beam size (\( \sigma_y \))
- \( N_U / N_{D2} \) for relative offset (\( \Delta_y \))
$N_{D1}/N_{all}$ and $N_U/N_{D2}$ were obtained with various beam parameters.

$N_{D1}/N_{all}$ vs. Vertical beam size ($\sigma_y$) [nm]

$N_U/N_{D2}$ vs. Vertical beam size ($\sigma_y$) [nm]

- $\sigma_x = 639$ [nm]
- $\sigma_x = 702.9$ [nm]
- $\sigma_x = 798.75$ [nm]
- $\sigma_x = 958.5$ [nm]

- $\Delta_y = 0$
- $\Delta_y = 0.2$
- $\Delta_y = 0.4$

$N_{D1}/N_{all}$ and $N_U/N_{D2}$ change as a function of the beam parameters.
Variable : $1/N_{\text{all}}$, $1/E_{\text{dep all}}$

The total number of hits ($N_{\text{all}}$) and total energy deposit ($E_{\text{dep all}}$) have information on the beam parameters.

$1/N_{\text{all}}$ vs. Vertical beam size ($\sigma_y$) [nm]

- $\sigma_x = 639$ [nm]
- $\sigma_x = 702.9$ [nm]
- $\sigma_x = 798.75$ [nm]
- $\sigma_x = 958.5$ [nm]

1/$N_{\text{all}}$ and 1/$E_{\text{dep all}}$ change as a function of the $\sigma_x$ and $\sigma_y$. 
Reconstruction of beam parameters

8 measurement variables were prepared.

- **Pair-monitor** … $R_{\text{max}}, \frac{N_{D1}}{N_{\text{all}}}, \frac{N_{U}}{N_{D2}}, \frac{1}{N_{\text{all}}}$
- **BeamCal** … $R_{\text{ave}}, \frac{N_{D}}{N_{\text{all}}}, \frac{N_{U}}{N_{D}}, \frac{1}{E_{\text{dep}}_{\text{all}}}$

Matrix components were determined by the fitting with the second order polynomials

$\begin{pmatrix}
R_{\text{max}} \\
\vdots \\
R_{\text{ave}}
\end{pmatrix} = \begin{bmatrix} A \end{bmatrix} \begin{pmatrix}
\sigma_x \\
\sigma_y \\
\Delta_y
\end{pmatrix} + \begin{pmatrix}
\sigma_x \\
\sigma_y \\
\Delta_y
\end{pmatrix} \begin{bmatrix} B \end{bmatrix}$

Beam parameters were reconstructed.

$X \equiv \begin{pmatrix}
\sigma_x \\
\sigma_y \\
\Delta_y
\end{pmatrix} = [A + X^T B]^{-1} M$
The performance was compared among three cases.

The combined analysis provides more precise measurement.
The accuracy of all the beam parameters is as follows.

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<td>3.2 %</td>
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<td>2.8 %</td>
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<td>10.1%</td>
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<td>9.4 %</td>
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The combined analysis provides more precise measurement for all the beam parameters.
Summary

- Pair-monitor and BeamCal measure the beam profile at IP.
  - Pair-monitor: silicon pixel detector to measure the hit count.
  - BeamCal: calorimeter to measure the energy deposit.

- The combined analysis with BeamCal was performed.
- Beam parameters ($\sigma_x$, $\sigma_y$, $\Delta_y$) are reconstructed using the Taylor matrix method (second order).

### Measurement accuracy

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The combined analysis can provides more precise measurement.
Backup
Matrix method for reconstruction

- Inverse matrix of a non-square matrix $A$ is defined as follows.

\[
A^{-1} \equiv \left( A^T A \right)^{-1} A^T
\]

\[
\Rightarrow A^{-1} A = \left( A^T A \right)^{-1} A^T A = 1
\]
$R_{\text{ave}} \equiv \frac{\sum R_i \times E_{\text{dep}_i}}{\sum E_{\text{dep}_i}}$

(R$_i$ is the radius of the i-th cell)

$R_{\text{max}}$ [cm] v.s.
Horizontal beam size ($\sigma_x$) [nm]

$R_{\text{ave}}$ [cm] v.s.
Horizontal beam size ($\sigma_x$) [nm]

$\Delta_y = 0$
$\Delta_y = 0.2$
$\Delta_y = 0.4$
Azimuthal distribution

The measurement variable was defined.

\[ N_U / N_{D2} \]
Variable: $N_{D1}/N_{all}$, $N_{U}/N_{D2}$

$N_{D1}/N_{all}$ v.s. Vertical beam size ($\sigma_y$) [nm]

$N_{U}/N_{D2}$ v.s. Vertical beam size ($\sigma_y$) [nm]

$\sigma_x = 639$ [nm]
$\sigma_x = 702.9$ [nm]
$\sigma_x = 798.75$ [nm]
$\sigma_x = 958.5$ [nm]

$\Delta y = 0$
$\Delta y = 0.2$
$\Delta y = 0.4$
Variable: $1/N_{all}$, $1/E_{dep_{all}}$

$1/E_{dep_{all}}$ v.s.
Vertical beam size ($\sigma_y$) [nm]

$\sigma_x = 639$ [nm]
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$\sigma_x = 798.75$ [nm]
$\sigma_x = 958.5$ [nm]

$\Delta_y = 0$
$\Delta_y = 0.2$
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Result \((\sigma_x)\)

- **BeamCal**
- **Pair-monitor**
- **Pair-monitor + BeamCal**

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**Vertical beam size [nm]**

- \(-30\) to \(30\)
Result ($\Delta_y$)

**BeamCal**

- $\sigma_x$
  - 639 [nm]
  - 702.9 [nm]
  - 766.8 [nm]
  - 798.75 [nm]
  - 830.7 [nm]
  - 958.5 [nm]

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**Pair-monitor**

- $\sigma_x$
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  - 702.9 [nm]
  - 766.8 [nm]
  - 798.75 [nm]
  - 830.7 [nm]
  - 958.5 [nm]

**Pair-monitor + BeamCal**

- $\sigma_x$
  - 639 [nm]
  - 702.9 [nm]
  - 766.8 [nm]
  - 798.75 [nm]
  - 830.7 [nm]
  - 958.5 [nm]