Performance Study of Pair-monitor (for ILD)

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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).

\[
\text{Relative offset } \Delta_y = \frac{\delta_y}{\sigma_y}
\]
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.
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)

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

\[= AX + X^T BX + \cdots\]

The beam parameters are reconstructed by the inverse matrix.

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

8 measurement variables were defined.

<table>
<thead>
<tr>
<th>Pair-monitor</th>
<th>BeamCal</th>
</tr>
</thead>
<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>$1/E_{\text{dep all}}$</td>
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</table>

- **Spread**
- **Ratio of the particular region**
- **Total hit or energy deposited**

We introduce above measurement variables.
The spread of the pair B.G. distribution changes, according to the transverse momentum of the pairs.

**Spread of pair B.G. distribution**

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

**Pt distribution at IP**

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

\[
R_{\text{ave}} = \frac{\sum R_i \times E_{\text{dep}_i}}{\sum E_{\text{dep}_i}}
\]

(R_i is the radius of the i-th cell)
R_{max} and R_{ave} were obtained with various beam parameters.

R_{max} [cm] v.s. Horizontal beam size (σ_x) [nm]

R_{ave} [cm] v.s. Horizontal beam size (σ_x) [nm]

σ_y = 5.7 [nm]
σ_y = 8.55 [nm]
σ_y = 11.4 [nm]
σ_y = 17.1 [nm]

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

**φ distribution at IP**

\[ \sigma_y = 5.7 \text{ [nm]} \]
\[ \sigma_y = 17.1 \text{ [nm]} \]

The measurement variables were defined from the pair-monitor.

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

$N_{D1}/N_{all}$ 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]

$\Delta y = 0$
$\Delta y = 0.2$
$\Delta y = 0.4$

$N_{D1}/N_{all}$ and $N_{U}/N_{D2}$ change as a function of the beam parameters.
The total number of hits ($N_{all}$) and total energy deposit ($E_{dep\ all}$) have information on the beam parameters.

$$\frac{1}{N_{all}} \text{ v.s. Vertical beam size ($\sigma_y$) [nm]}$$

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

$$\frac{1}{N_{all}} \text{ v.s. Vertical beam size ($\sigma_y$) [nm]}$$

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

$\frac{1}{N_{all}}$ and $\frac{1}{E_{dep\ all}}$ 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

$$[ \begin{array}{c} R_{\text{max}} \\ \vdots \\ R_{\text{ave}} \end{array} ] = \mathbf{A} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \Delta_y \end{pmatrix} + \begin{pmatrix} \sigma_x \\ \sigma_y \\ \Delta_y \end{pmatrix} \mathbf{B}$$

Beam parameters were reconstructed.

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

The combined analysis provides more precise measurement.

Results ($\sigma_y$)

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<thead>
<tr>
<th>[ $\sigma_x$ ]</th>
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**Results (\(\sigma_x, \sigma_y, \Delta_y\))**

The accuracy of all the beam parameters is as follows.

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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.

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

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

(\( R_i \) is the radius of the i-th cell)

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

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

\( \Delta_y = 0 \)
\( \Delta_y = 0.2 \)
\( \Delta_y = 0.4 \)
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]

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$\sigma_x = 958.5$ [nm]
Variable: $1/N_{\text{all}}$, $1/E_{\text{dep all}}$

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

Vertical beam size ($\sigma_y$) [nm]

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Result ($\sigma_x$)

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BeamCal

Pair-monitor

Pair-monitor + BeamCal
Result ($\Delta_y$)

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