Track Resolution Studies with the “LiC Detector Toy”
Monte Carlo Tool

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LiC is a simple but powerful and flexible software tool, written in MATLAB, for basic
detector design studies (geometries, material budgets). It is based on a helix track
model including multiple scattering, and uses a Kalman filter for track fitting. We use
this tool for comparing two variants of the LDC and one of the SiD layout, by studying
track resolutions ($\Delta p_T / p_T$, $\Delta p_T / p_T^2$, transverse and spatial impact parameters) over
the transverse momentum range $2.5 < p_T < 35$ GeV in the barrel region. Investigation
of the forward/backward region is so far for LDC only.

1 The Monte Carlo Tool

A software tool for detector design, written in MATLAB®, has been developed for tracking
studies at the ILC. It aims at investigating the resolution of reconstructed track parameters
in the vertex region for the purpose of comparing and optimizing the track sensitive devices
and the material budgets of various detector set-ups. The detector model corresponds to a
collider experiment with a solenoid magnet and a helix track model. The geometric surfaces
are either cylinders (barrel region) or planes (forward/backward region). Material causing
multiple scattering is assumed to be concentrated within thin layers.

A simplified simulation performs tracking with inclusion of multiple scattering, and simulates
detector measurements including systematic and/or stochastic inefficiencies and uniform
or Gaussian observation errors. Supported are Si strips (single or double sided, with any stereo angle),
pixel detectors, and a TPC – all described by a simple text file. This is followed by track reconstruction by means of a Kalman filter [1], the fitted parameters and
covariances being evaluated at the inner surface of the beam tube.

For a thorough description of its functionality and usage see [2].

2 Track resolution study

This study is based on about $2 \times 18,700$ (LDC barrel), 22,400 (SiD barrel) and 8,840 (LDC
forward/backward) tracks, respectively, simulated and fitted by the “LiC Detector Toy”
program. Definitions of the “barrel” and “forward/backward” regions in terms of the dip
angle $\lambda \equiv \pi / 2 - \theta_{pole}$ are given in section 3.

The true and fitted track data are passed to and further analyzed by a Java program,
running within JASP3 and using AIDA [3]; calculating the deviations of fitted w.r.t. true
transverse momenta $\Delta p_T = (p_T^{true} - p_T)$, and the impact parameters $\delta_T$ and $\delta_0$ (transverse
and in space, respectively); histogramming $\Delta p_T / p_T$, $\Delta p_T / p_T^2$, $\delta_T$ and $\delta_0$ for separate intervals
of true $p_T$; extracting the rms or mean from each histogram; then using parametrizations
(subsection 2.2) to fit $\text{rms}(\Delta p_T / p_T)$, $\text{rms}(\Delta p_T / p_T^2)$, $\text{rms}(\delta_T)$, and $\text{mean}(\delta_0)$ as functions of the
central value of each $p_T$ interval – see figs. 1...4.

Section 3 presents preliminary results and conclusions.

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2.1 LDC and SiD detector descriptions

The geometry and material constants of the ILC “Large Detector” (LDC) and “Silicon Detector” (SiD) concepts have been taken from [4], and are summarized below.

<table>
<thead>
<tr>
<th>#</th>
<th>R [mm]</th>
<th>Z [mm]</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.8</td>
<td>idem</td>
<td>idem</td>
</tr>
<tr>
<td>2</td>
<td>1.8</td>
<td>idem</td>
<td>idem</td>
</tr>
<tr>
<td>3</td>
<td>1.8</td>
<td>idem</td>
<td>idem</td>
</tr>
<tr>
<td>4</td>
<td>1.8</td>
<td>idem</td>
<td>idem</td>
</tr>
</tbody>
</table>

Barrel region restricted to $|\lambda| < 20^\circ$, in order to avoid the “supporting membranes” of the VXD.

2.2 Parametrization of track resolutions

- The relative errors of the transverse momentum due to the magnet spectrometer resolution or caused by multiple scattering, respectively, are:
  \[ \sigma(p_T)/p_T = A \cdot p_T \quad \text{and} \quad \sigma(p_T)/p_T = B \cdot \sqrt{1 + (m/P)^2} \approx B \]
- Above terms are expected to add quadratically. However, for $p_T < 50$ GeV, a simpler linear addition fits the data quite well and has been used:
  \[ \sigma(p_T)/p_T = A \cdot p_T + B, \quad \text{thus} \quad \sigma(1/p_T) \equiv \sigma(p_T)/p_T^2 = A + B/p_T \]
- For lack of a theoretical model, the errors of the impact parameters w.r.t. the true vertex are heuristically parametrized for $p_T > 2.5$ GeV as:
  \[ \sigma(\delta_{T,0}) = a + b \cdot e^{-p_T/c} \]  
  (for high $p_T$, the asymptotic value = a)

In the forward/backward region, only linear parametrizations in $p_T$ have been used.

2.3 LDC and SiD track resolutions

- **LDC and SiD barrel regions** for $p_T = 1 \ldots 35$ GeV (figs. 1 \ldots 4 at left): the data points correspond to LDC $50 \times 50\mu m$ pixels (blue dots), LDC $25 \times 25\mu m$ pixels (red squares), and SiD $20 \times 20\mu m$ pixels (purple triangles), respectively, of the barrel vertex detectors - for a detailed description, see subsection 2.1.

- **LDC forward/backward regions** for $p_T = 1 \ldots 25$ GeV (figs. 1 \ldots 4 at right): the data points correspond to dip angle ranges of $81^\circ < |\lambda| < 81.5^\circ$ (blue dots), $81.5^\circ < |\lambda| < 82^\circ$ (red squares), and $82^\circ < |\lambda| < 82.5^\circ$ (purple triangles).

The values are averages over $p_T$ intervals of width 2.5 GeV. The error bars shown reflect only the statistics normalized to bin content.

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Fig. 1: $\text{rms}(\Delta p_T/p_T)$ vs. $p_T$ for barrel (left) and forward/backward (right) regions.

Fig. 2: $\text{rms}(\Delta p_T/p_T^2)$ [GeV$^{-1}$] vs. $p_T$ for barrel (left) and forward/backward (right) regions.

Fig. 3: $\text{rms}(\delta_T)$ [mm] vs. $p_T$ for barrel (left) and forward/backward (right) regions.

Fig. 4: mean($\delta_0$) [mm] vs. $p_T$ for barrel (left) and forward/backward (right) regions.

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3 Preliminary results

The results extracted from figs. 1...4 (subsection 2.3) are summarized below.

**Barrel regions** (LDC: $|\alpha| < 48^\circ$, SiD: $|\alpha| < 20^\circ$, $p_T = 2.5...35$ GeV):

<table>
<thead>
<tr>
<th>Detector, px size</th>
<th>rms($\Delta p_T/p_T$)</th>
<th>rms($\Delta p_T/p_T^2$) [GeV$^{-1}$]</th>
<th>rms($\delta_T$)$^a$</th>
<th>mean($\delta_0$)$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDC 50 $\times$ 50 $\mu m$</td>
<td>(4.6 $\cdot$ $p_T$ + 30.7) $\cdot$ 10$^{-3}$</td>
<td>(4.5 + 31.9)/$p_T$ $\cdot$ 10$^{-3}$</td>
<td>7.69 $\mu m$</td>
<td>9.56 $\mu m$</td>
</tr>
<tr>
<td>LDC 25 $\times$ 25 $\mu m$</td>
<td>(4.6 $\cdot$ $p_T$ + 28.5) $\cdot$ 10$^{-3}$</td>
<td>(4.6 + 29.5)/$p_T$ $\cdot$ 10$^{-3}$</td>
<td>4.29 $\mu m$</td>
<td>5.91 $\mu m$</td>
</tr>
<tr>
<td>SiD 20 $\times$ 20 $\mu m$</td>
<td>(2.4 $\cdot$ $p_T$ + 14.6) $\cdot$ 10$^{-3}$</td>
<td>(2.2 + 14.4)/$p_T$ $\cdot$ 10$^{-3}$</td>
<td>3.46 $\mu m$</td>
<td>6.46 $\mu m$</td>
</tr>
</tbody>
</table>

**Forward/backward regions** ($81^\circ < |\alpha| < 82.5^\circ$, $p_T = 2.5...25$ GeV):

| LDC $|\alpha|$ range | rms($\Delta p_T/p_T$) | rms($\Delta p_T/p_T^2$)$^b$ | rms($\delta_T$)$^b$ | mean($\delta_0$)$^b$ |
|----------------------|-----------------------|--------------------------|----------------|------------------|
| $81^\circ < |\alpha| < 81.5^\circ$ | (8.4 $\cdot$ $p_T$ - 2.83) $\cdot$ 10$^{-3}$ | 8.36 $\cdot$ 10$^{-3}$ GeV$^{-1}$ | 86.7 $\mu m$ | 70.7 $\mu m$ |
| $81.5^\circ < |\alpha| < 82^\circ$ | (5.7 $\cdot$ $p_T$ + 0.35) $\cdot$ 10$^{-3}$ | 5.80 $\cdot$ 10$^{-3}$ GeV$^{-1}$ | 70.3 $\mu m$ | 57.1 $\mu m$ |
| $82^\circ < |\alpha| < 82.5^\circ$ | (5.0 $\cdot$ $p_T$ + 3.65) $\cdot$ 10$^{-3}$ | 5.37 $\cdot$ 10$^{-3}$ GeV$^{-1}$ | 63.1 $\mu m$ | 53.4 $\mu m$ |

Preliminary conclusions:

In the barrel region and for transverse momenta $p_T < 35$ GeV, the momentum resolution benefits dramatically from the low material budget of LDC’s TPC; in contrast, SiD’s all-Si tracker suffers from accumulated multiple scattering. However, extrapolation to higher momenta shows a break-even at $p_T \approx 50$ GeV. – The transverse impact parameters reflect the pixel sizes of each vertex detector’s innermost layer(s).

In the forward/backward region $|\alpha| > 81^\circ$, the momentum resolution is sensitive to LDC’s forward tracker strips stereo angle: $\pm 45^\circ$ is a good compromise between optimal $R - \Phi$ and $R - z$ resolutions. For $|\alpha| > 82.5^\circ$ (not shown), track reconstruction suffers extremely from inefficiencies, and might require non-standard treatment.

Acknowledgments

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References

[4] Detector Outline Documents:

$^a$asymptotic value,
$^b$weighted average.

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