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 $\lambda \equiv \pi/2 - \vartheta_{polar}$ are given in section 3.

The true and fitted track data are passed to and further analyzed by a Java program, running within JAS3 and using AIDA [3]: calculating the deviations of fitted w.r.t. true transverse momenta $\Delta p_T = (p_T^{fitted} - p_T)$, and the impact parameters δ_T and δ_0 (transverse and in space, respectively); histogramming $\Delta p_T/p_T$, $\Delta p_T/p_T^2$, δ_T and δ_0 for separate intervals of true p_T; extracting the rms or mean from each histogram; then using parametrizations (subsection 2.2) to fit rms($\Delta p_T/p_T$), rms($\Delta p_T/p_T^2$), rms(δ_T), and mean(δ_0) as functions of the central value of each p_T interval – see figs. 1 . . . 4.

Section 3 presents preliminary results and conclusions.

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.

LDC Detector description

B_z = 4 Tesla; efficiency Si = 95%, TPC = 100%; errors in μm

BARREL	*R[mm]*	*Z_{min}[mm]*	*Z_{max}[mm]*	*Error distribution*	*d[X_o]*	*Remarks*
Beam pipe	14			passive	.0025	0.4 mm Be
VTX 1	16	-50	50	pads 50*50 (25*25) equ. distrib.	.002	wafer + ladder
VTX 2	26	-120	120	idem	idem	idem
VTX 3	37	idem	idem	idem	idem	idem
VTX 4	48	idem	idem	idem	idem	idem
VTX 5	60	idem	idem	idem	idem	idem
Support structures	90	-110	-90	passive	.070	arbitrary
idem	idem	90	110	passive	idem	idem
SIT 1	150	-150	150	strips 2*50	.0175	0°, 10°
SIT 2	290	-360	360	idem	idem	idem
TPC inn. wall	340	-2160	2160	passive	0.140	
196 pad rings	<1580	idem	idem	$\sqrt{(\sigma_1^2 + \sigma_2^2 \Delta z)}$ $\sigma_{1,2}$ = 50, 3.8 in RΦ	196 * 1.25E-5	$\sigma_{1,2}$ = 15, 58 in z

FORWARD	*Z[mm]*	*R_{min}[mm]*	*R_{max}[mm]*	*Error distribution*	*d[X_o]*	*Remarks*
FTD 1	180	40.0	138	pads 50*300	.01	
FTD 2	300	47.5	140	idem	idem	
FTD 3	450	57.5	280	idem	idem	
FTD 4	800	87.5	idem	strips 2*90	idem	± 45°
FTD 5	1200	122.5	idem	idem	idem	idem
FTD 6	1550	157.5	idem	idem	idem	idem
FTD 7	1900	187.5	idem	idem	idem	idem

SiD Detector description

B_z = 5 Tesla; efficiency Si = 95%; errors in μm

BARREL	*R[mm]*	*Z_{min}[mm]*	*Z_{max}[mm]*	*Error distribution*	*d[X_o]*	*Remarks*
Beam pipe	12	-62.5 + conus	62.5 + conus	passive	.00253	0.4 mm Be + Ti
VXD 1	14.6	-62.5	62.5	pads 20*20 equ. distrib.	.00202	wafer + ladder
VXD 2	22.6	idem	idem	idem	idem	idem
VXD 3	35.4	idem	idem	idem	idem	idem
VXD 4	48.0	idem	idem	idem	idem	idem
VXD 5	60.4	idem	idem	idem	idem	idem
Dbl. support cylinders	168.7 184.2	-868.8 -894.3	868.8 894.3	passive	2 * .00152	dbl. wall C fibre
TRK 1	218.0	-558.0	558.0	strips 50	.00800	single
TRK 2	468.0	-825.0	825.0	idem	idem	idem
TRK 3	718.0	-1083.0	1083.0	idem	idem	idem
TRK 4	968.0	-1347.0	1347.0	idem	idem	idem
TRK 5	1218.0	-1606.0	1606.0	idem	idem	idem

FORWARD	*Z[mm]*	*R_{min}[mm]*	*R_{max}[mm]*	*Error distribution*	*d[X_o]*	*Remarks*
not implemented so far						

Barrel region restricted to $|\lambda| < 20^o$, 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:
  $\sigma(p_T)/p_T = A \cdot p_T$ and $\sigma(p_T)/p_T = B \cdot \sqrt{1 + (m/P)^2} \approx B$
- 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:
  $\sigma(p_T)/p_T = A \cdot p_T + B,$ thus $\sigma(1/p_T) \equiv \sigma(p_T)/p_T^2 = A + B/p_T$
- 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 ... 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), respectiveley, 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 ... 4 at right):
  the data points correspond to dip angle ranges of $81^o < |\lambda| < 81.5^o$ (blue dots), $81.5^o < |\lambda| < 82^o$ (red squares), and $82^o < |\lambda| < 82.5^o$ (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.

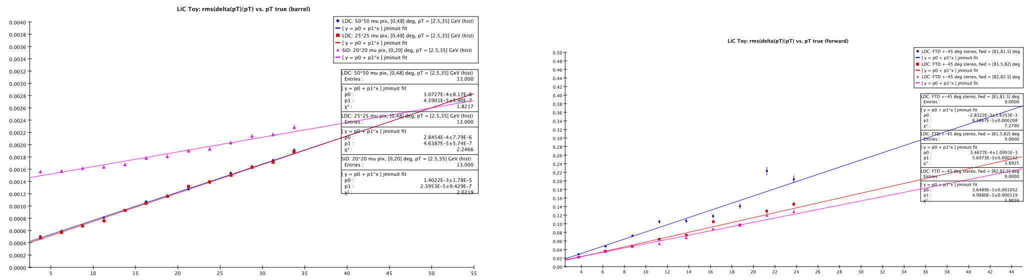

Fig. 1: rms($\Delta p_T/p_T$) vs. p_T for barrel (left) and forward/backward (right) regions.

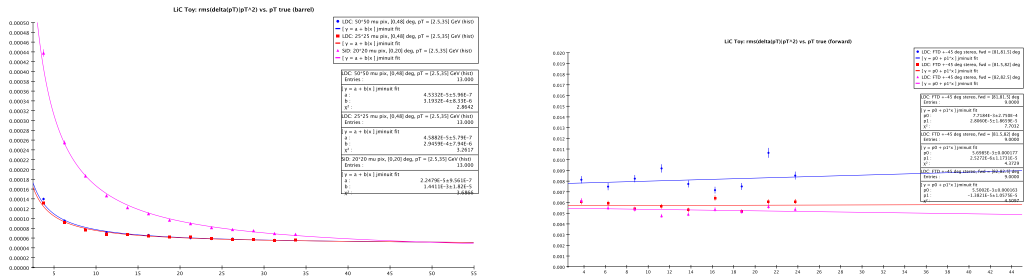

Fig. 2: rms($\Delta p_T/p_T^2$) [GeV^{-1}] vs. p_T for barrel (left) and forward/backward (right) regions.

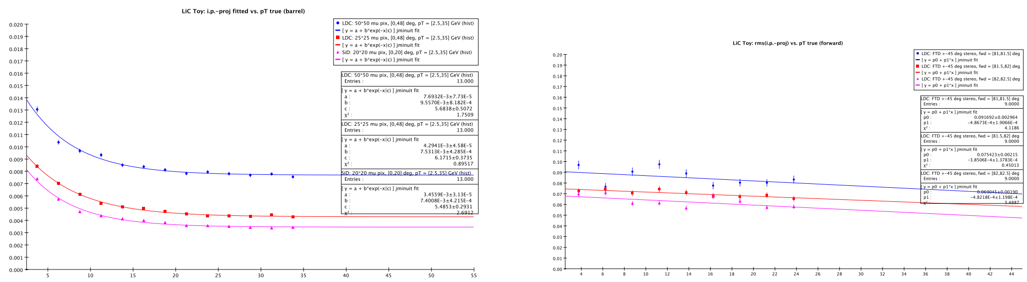

Fig. 3: rms(δ_T) [mm] vs. p_T for barrel (left) and forward/backward (right) regions.

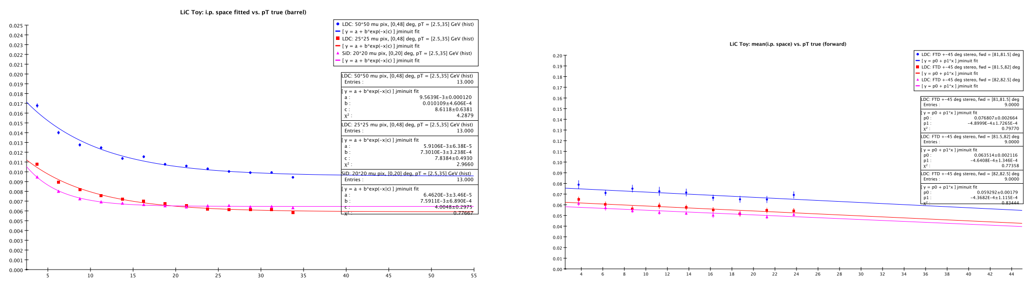

Fig. 4: mean(δ_0) [mm] vs. p_T for barrel (left) and forward/backward (right) regions.

3 Preliminary results

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

Barrel regions (LDC: $|\lambda| < 48^o$, SiD: $|\lambda| < 20^o$), $p_T = 2.5 \ldots 35$ GeV:

Detector, px size	rms($\Delta p_T/p_T$)	rms($\Delta p_T/p_T^2$) [GeV^{-1}]	rms(δ_T)[a]	mean(δ_0)[a]
LDC $50 \times 50\mu$m	$(4.6 \cdot p_T + 30.7) \cdot 10^{-5}$	$(4.5 + 31.9/p_T) \cdot 10^{-5}$	7.69 μm	9.56 μm
LDC $25 \times 25\mu$m	$(4.6 \cdot p_T + 28.5) \cdot 10^{-5}$	$(4.6 + 29.5/p_T) \cdot 10^{-5}$	4.29 μm	5.91 μm
SiD $20 \times 20\mu$m	$(2.4 \cdot p_T + 140.) \cdot 10^{-5}$	$(2.2 + 144./p_T) \cdot 10^{-5}$	3.46 μm	6.46 μm

Forward/backward regions ($81^o < |\lambda| < 82.5^o$), $p_T = 2.5 \ldots 25$ GeV:

LDC $|\lambda|$ range	rms($\Delta p_T/p_T$)	rms($\Delta p_T/p_T^2$)[b]	rms(δ_T)[b]	mean(δ_0)[b]
$81^o < |\lambda| < 81.5^o$	$(8.4 \cdot p_T - 2.83) \cdot 10^{-3}$	$8.36 \cdot 10^{-3}$ GeV^{-1}	86.7 μm	70.7 μm
$81.5^o < |\lambda| < 82^o$	$(5.7 \cdot p_T + 0.35) \cdot 10^{-3}$	$5.80 \cdot 10^{-3}$ GeV^{-1}	70.3 μm	57.1 μm
$82^o < |\lambda| < 82.5^o$	$(5.0 \cdot p_T + 3.65) \cdot 10^{-3}$	$5.37 \cdot 10^{-3}$ GeV^{-1}	63.1 μm	53.4 μm

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

Acknowledgments

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References

[1] M. Regler, R. Frühwirth and W. Mitaroff: Int.J.Mod.Phys. **C7**, 4 (1996) 521 - 542.

[2] M. Regler, M. Valentan and R. Frühwirth: *The LiC Detector Toy Program*, Proc. 11^{th} Vienna Conf. on Instrumentation (VCI) 2007, Nucl.Instr.Meth. **A** (in print).
User's Guide: `http://wwwhephy.oeaw.ac.at/p3w/ilc/reports/LiC_Det_Toy/Reports/UserGuide.pdf`

[3] JAS3: `http://jas.freehep.org/`, AIDA: `http://aida.freehep.org/`

[4] Detector Outline Documents:
LDC (July 2006): `http://www.ilcldc.org/documents/dod/outline.pdf`
SiD (May 2006): `http://hep.uchicago.edu/~oreglia/siddod.pdf`

[a] asymptotic value,
[b] weighted average.