Detectors for the Future Linear Collider Experiments

M. Iwasaki
University of Tokyo
Detector Requirements for LC

**Vertex Detector**

physics motivates excellent efficiency and purity
large pair background from beamstrahlung
→ large solenoidal field (≥ 3 Tesla)

pixelated detector [\((20 \, \mu m)^2 \rightarrow 2500 \, \text{pixels/mm}^2\)]

min. inner radius (< 1.5 cm), ~5 barrels, < 4 \(\mu\)m resol,
thickness < 0.2 \% \(X_0\)

**Calorimetry**

excellent jet reconstruction

eg. W/Z separation

use energy flow for best resolution

(calorimetry and tracking work together)

fine granularity and minimal Moliere radius

charge/neutral separation → large BR^2
Tracking
Robust in Linear Collider environment
Isolated particles (e charge, \( \mu \) momentum)
Charge particle component of jets
jet energy flow measurements
Assists vertex detector with heavy quark tagging
Forward tracking (susy and lum measurement)

Muons
High efficiency with small backgrounds
Secondary role in calorimetry ("tail catcher")
There are many important things we should consider for LC detectors:

but today, I’ll focus on

1) Vertex detector and 2) Calorimeter (EM)

These are the key detectors for

Heavy-Flavor tagging → Vertex Detector
Jet reconstruction → Calorimeter

In this talk, I’ll show

1) Current detector designs
2) Vertex-detector
3) Calorimeter
Detectors which have been studied

- **TESLA**
  - $R = 7.4\,\text{m}$, $B = 4\,\text{T}$

- **JLC**
  - $R = \sim 8\,\text{m}$, $B = 2-3\,\text{T}$

- **NLC - L**
  - $R = 6.2\,\text{m}$, $B = 3\,\text{T}$

- **NLC - S**
  - $R = 3.7\,\text{m}$, $B = 6\,\text{T}$
NLC- L
Large detector
Large tracking volume \(\rightarrow\) Good tracking resolution
Large radius calorimeter
\(\rightarrow\) Large \(BR^2\) ... Good charged/neutral separation
Large volume limits size of B filed
\(\rightarrow\) may not settle VXD so close to IP

NLC- S
Small detector
Small volume detector \(\rightarrow\) Allow high B field
Small radius calorimeter
\(\rightarrow\) allows high granularity (Energy-Flow CAL)
High B field \(\rightarrow\) Can close VXD to IP
2) Vertex Detector

Physics of Linear Collider demands the best possible vertex detector performance

→ Clean separation of b, c, and uds jets and \( \tau \)'s

Optimizing flavor tag

Good impact parameter resolution

→ SLD-type Vertex Detector:
  
  **CCD (or Active pixels?)**
  
  Thin material
  
  Small inner radius ...BG reduction → High B-field
Experience of the SLD CCD Vertex Detector
SLD Vertex Detector (VXD3)

- Total # of pixels: 307M
- Pixel cell size: 20µm x 20µm
- Rad. Length: 0.40%/layer (2.1% total)
- Inner & Outer radius: 28.0 mm 48.3 mm
- Acceptance: |cosθ|< 0.85
- Single hit resolution: 3.5 µm

Using the unique features of the SLD:

1) High resolution CCD vertex detector
   impact parameter resolution of 7.8 µm (rφ) 9.7µm(rz)

2) Small and stable beam spot
   primary vertex resolution s(rφ) = 4 µm

high performance flavor-tagging method is developed
→ Mass-tag method based on the topological vertexing
SLD Vertex Detector

OPAL $\mu$VTX

Inner & Outer radius: 28.0 mm  48.3 mm
Flavor-tagging $\rightarrow$ Mass-tag method

based on the topological vertex finding

1. Reconstruct Secondary Vertex
2. Form 'P_T-corrected mass' of SV
3. Identify heavy-quark signals with $M_{\text{corr}}$ based on the topological vertex finding

$$M_{\text{corr.}} = \sqrt{M_{\text{vtx}}^2 + |P_T^{\text{vtx}}|^2} + |P_T^{\text{vtx}}|$$
b-tagging: $P_T$ corrected mass > 2.0 GeV

efficiency = 50%, purity = 98%
B-tag performance
Note: LEP exp.s have 10 times higher statistics than SLD!
c-tagging

In general, c-tagging is difficult
→ strongly depends on the detector performance

0.5 GeV < \( P_T \) corrected mass < 2.0 GeV
+ 2-dim. Cut on vertex mass and momentum

efficiency = 16%  purity = 70%
R_c Measurements (Winter-2001)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH Lepton</td>
<td>0.1675±0.0062±0.0103</td>
</tr>
<tr>
<td>ALEPH c-counting</td>
<td>0.1738±0.0047±0.0113</td>
</tr>
<tr>
<td>DELPHI c-counting</td>
<td>0.1692±0.0047±0.0097</td>
</tr>
<tr>
<td>OPAL c-counting</td>
<td>0.167±0.011±0.012</td>
</tr>
<tr>
<td>ALEPH D* incl/excl</td>
<td>0.166±0.012±0.009</td>
</tr>
<tr>
<td>DELPHI D* incl/excl</td>
<td>0.161±0.010±0.009</td>
</tr>
<tr>
<td>OPAL D* incl/excl</td>
<td>0.180±0.010±0.012</td>
</tr>
<tr>
<td>ALEPH D excl/excl</td>
<td>0.173±0.014±0.009</td>
</tr>
<tr>
<td>SLD Multi-tag</td>
<td>0.1757±0.0032±0.0024</td>
</tr>
<tr>
<td>World Average</td>
<td>0.1729±0.0032</td>
</tr>
</tbody>
</table>

Just outstanding!
In 1996, VXD3 was damaged by a large SR dose in abnormal beam conditions.
Reducing Operating temp from 220K to 185K

..Then fix it!!
**Improvement Proposed For NLC**

<table>
<thead>
<tr>
<th>Feature</th>
<th>SLD VXD3</th>
<th>NLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer thickness</td>
<td>0.4% $X_0$</td>
<td>0.12% $X_0$</td>
</tr>
<tr>
<td>Inner radius</td>
<td>28 mm</td>
<td>12 mm*</td>
</tr>
<tr>
<td># layers</td>
<td>3 layers</td>
<td>5 layers</td>
</tr>
<tr>
<td>Read out</td>
<td>5 MHz</td>
<td>50 MHz</td>
</tr>
<tr>
<td>Imp. resolution</td>
<td>$\sim 10 \ \mu m$</td>
<td>$\sim 3 \ \mu m$</td>
</tr>
</tbody>
</table>

*Large may have larger BG*

**Diagram:**
- **CCD**
- **Dead Region 40µm**
- **Targets for optical survey**
- **Beryllium substrate (Omega-beam)**
- **Kapton/Copper stripline**
NLC Vertex Detector

670,000,000 pixels [20x20x20 (µm)^3]
3 µm hit resolution
inner radius = 1.2 cm
5 layer → stand-alone tracking

Cos θ = 0.98
...Do we need the ~1cm radius vertex detector for LC?
c-jet tagging

T. Abe
3) Calorimeter

In the future linear collider experiments, many physics processes have multi jets in the final states → Good Jet reconstruction is essential

Strategies for the jet measurement

1) Tracking + $E_{EM}$ (+$E_{HAD}$ correction)
   .. Energy Flow Algorithm .. ALEPH
   High B filed, Large radius
   Fine granularity to separate neutral / charged

2) $E_{EM}$ + $E_{HAD}$ (+tracking correction) .. ZEUS/H1
   Low B filed, Compensated response
Av. momentum of charged particle $\sim 2.4$ GeV @ $E_{\text{CM}} = 500$ GeV

$\ldots \sigma_p(\text{Tracker})$ is better than $\sigma_E(\text{Calorimeter})$

Energy Flow Type Calorimeter is important for LC

Energy-Flow Calorimeter... Fine segmentation $\text{CAL}$

$\rightarrow \text{NLC-S (& TESLA?)}$

**NLC-S detector parameter:**

- W-Si EM cal granularity: $3.7$ mrad (5mm segmentation)
- # layers: 30 layer
- inner radius: 127 cm
- $B = 5.0$ Tesla
Jet Reconstruction ... Energy Flow method
   We use Tracker for charged particles
   Calorimeters for neutral particles

For example, in $e^+e^-$ → $\bar{t}t$ (6jets,4jets) events,

- Charged particles carry ~60% of event energy → Tracker
- Photons: 20% → EM Cal
- Neutral hadrons: 10% → HAD Cal
- Neutrino: 10% cannot detect

($E_{cm} = 500$GeV, Generator level)

At first, $\gamma$ reconstruction in EM CAL is important!!
γ selection by transverse information

To separate Charged/Neutral Clusters we see track-cluster matching

1) Extrapolate Charged tracks to the Cluster radius,
2) Associate the nearest track to the cluster

Apply a cut: Track-cluster distance > 2.5 cm
→ γ selection π 48% ε 98% (for Ecls>0.2GeV clusters : NLC-S)
3-2) $\gamma$ selection by longitudinal information

It is useful to separate EM particles / hadron by seeing longitudinal Edeposit information.

### Longitudinal energy deposit shape

- **Photon**
  - Distance from CAL surface (cm)
  - Histogram showing energy deposit for photon events.

- **Electron**
  - Distance from CAL surface (cm)
  - Histogram showing energy deposit for electron events.

- **Hadron**
  - Distance from CAL surface (cm)
  - Histogram showing energy deposit for hadron events.

- **Muon**
  - Distance from CAL surface (cm)
  - Histogram showing energy deposit for muon events.

- **Scattered**
  - Distance from CAL surface (cm)
  - Histogram showing energy deposit for scattered events.
### Summary of $\gamma$ selection (NLC-S detector)

<table>
<thead>
<tr>
<th>Cut Type</th>
<th>$\gamma$</th>
<th>Not $\gamma$</th>
<th>Scattered</th>
<th>Purity</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecl &gt; 0.2 GeV</td>
<td>33974</td>
<td>33471</td>
<td>27999</td>
<td>36%</td>
<td>98%</td>
</tr>
<tr>
<td>Tack-cluster cut</td>
<td>33170</td>
<td>8352</td>
<td>26907</td>
<td>48%</td>
<td>98%</td>
</tr>
<tr>
<td>Longitudinal cuts</td>
<td>29148</td>
<td>2316</td>
<td>2760</td>
<td>85%</td>
<td>86%</td>
</tr>
</tbody>
</table>

Overall $\gamma$ selection performance ...

$\sim$85% purity, $\sim$85% efficiency
Mass reconstruction

Using the energy flow object (track+neutral clusters), reconstruct W and Top-quark in $e^+e^- \rightarrow t\bar{t}$ events (6& 4jets)

<table>
<thead>
<tr>
<th></th>
<th>W mass</th>
<th>error</th>
<th>Top mass</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track + $\gamma$</td>
<td>67.1±15.9 GeV</td>
<td>(28%)</td>
<td>141.0±33.5</td>
<td>(24%)</td>
</tr>
<tr>
<td>Track + $\gamma$ (true)</td>
<td>70.2±16.9</td>
<td>(24%)</td>
<td>147.0±31.7</td>
<td>(22%)</td>
</tr>
<tr>
<td>Track + $\gamma$ (true) + $h^0$(true)</td>
<td>77.2±15.1</td>
<td>(20%)</td>
<td>159.7±30.7</td>
<td>(19%)</td>
</tr>
</tbody>
</table>

No selection cut (Xjet cut for example) applied

True-$\gamma$/selected-$\gamma$ difference ... 2~3 %

$\rightarrow$ We get very good photon-selection performance
Summary

1) Vertex Detector
   SLD-type Vertex Detector is required for LC
   ... CCD, small inner radius
   $R_{\text{inner}}=1\text{cm}$ detector is important for c-tagging

2) Calorimeter
   Energy-Flow type Detector is important
   Fine granularity/segmentation in both longitudinal
   and transverse provides
   excellent $\gamma$ reconstruction performance
There are several detector parameters proposed:

- **High - B**: NLC-S
- **Medium - B**: JLC, TESLA, NLC-L

Realistic BG study for the Vertex detector is necessary (if we want $R_{\text{inner}}(\text{VTX})=1\text{cm}$):

- **Energy-flow type CAL**: NLC-S, TESLA
- **general-type CAL**: JLC, NLC-L

Detailed jet reconstruction study is important.
Beam Delivery System Simulation by GEANT4

→ Just started !!

By K. Tanabe