Linear Collider Detectors

Jim Brau
Univ. of Oregon

Fermilab
April 5, 2002

• Many open issues for LC detectors

• Physics goals involve low event rates with relatively low backgrounds
  - opportunity for novel approaches
The “next” Linear Collider proposals include plans to deliver a few hundred fb\(^{-1}\) of integrated lum. per year.

<table>
<thead>
<tr>
<th></th>
<th>TESLA (DESY-Germany)</th>
<th>JLC-C (Japan)</th>
<th>NLC/JLC-X (SLAC/KEK-Japan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_{\text{design}}) ((10^{34}))</td>
<td>3.4 → 5.8</td>
<td>0.43</td>
<td>2.2 → 3.4</td>
</tr>
<tr>
<td>(E_{\text{CM}}) ((\text{GeV}))</td>
<td>500 → 800</td>
<td>500</td>
<td>500 → 1000</td>
</tr>
<tr>
<td>Eff. Gradient ((\text{MV/m}))</td>
<td>23.4 → 35</td>
<td>34</td>
<td>70</td>
</tr>
<tr>
<td>RF freq. ((\text{GHz}))</td>
<td>1.3</td>
<td>5.7</td>
<td>11.4</td>
</tr>
<tr>
<td>(\Delta t_{\text{bunch}}) ((\text{ns}))</td>
<td>337 → 176</td>
<td>2.8</td>
<td>1.4</td>
</tr>
<tr>
<td>#bunch/train</td>
<td>2820 → 4886</td>
<td>72</td>
<td>190</td>
</tr>
<tr>
<td>Beamstrahlung ((%))</td>
<td>3.2 → 4.4</td>
<td></td>
<td>4.6 → 8.8</td>
</tr>
</tbody>
</table>

* US and Japanese X-band R&D cooperation, but machine parameters may differ.
There is perception that Linear Collider Detectors are trivial

Not true!

But requirements are orthogonal to hadron collider requirements

Here are some comparisons

**Tracker thickness:**
- CMS: $0.30 \times X_0$
- ATLAS: $0.28 \times X_0$
- LC: $0.05 \times X_0$

**Vertex Detector layer thickness**
- CMS: $1.7 \% X_0$
- ATLAS: $1.7 \% X_0$
- LC: $0.06\% X_0$
Detector Requirements

Vertex Detector granularity

- CMS: 39 Mpixels
- ATLAS: 100 Mpixels
- LC (Tesla): 800 Mpixels

ECAL granularity (detector elements)

- CMS: $76 \times 10^3$
- ATLAS: $120 \times 10^3$
- LC(Tesla): $32 \times 10^6$

Unburdened by high radiation and high event rate, the LC can use

- 6 times less material in tracker
- vxd 3-6 times closer to IP
- 35 times smaller pixels and 30 times thinner vxd layers
- > 200 times higher ECAL granularity (if it’s affordable)
IR Issues

Time structure

NLC (JLC)

Tesla
IR Issues

Time structure

**NLC (JLC)**
190 bunches/train $\Rightarrow$ 1.4 ns bunch spacing
$\Rightarrow$ crossing angle (20 mrad) - (8 mrad for JLC)
might want to time-stamp within train?

**Tesla**
2820 bunches/train $\Rightarrow$ 950 $\mu$sec long
no crossing angle, but could have one
very much higher duty cycle (how to deal with?)
IR Issues

Solenoid effects
transverse component of solenoid must be compensated - straightforward

IR Layout
$L^* = 3.8$ m

Masks
M1 - W/Si
M2 - W
Low-Z
IR Issues

Small spot size issues
   nm vertical stability required
   ⇒ permanent magnets for QD0 and QF1
   passive compliance + active suppression
   15 ns response within bunch train (NLC)

Beam-beam interaction
   broadening of energy distribution (beamstrahlung)
   ~5% of power at 500 GeV
   backgrounds
     e⁺e⁻ pairs
     radiative Bhabhas
     low energ tail of disrupted beam
     neutron “back-shine” from dump
     hadrons from gamma-gamma
IR Issues

3 Tesla

\( e^+e^- \) pairs

Hits/bunch train/mm\(^2\) in VXD, and photons/train in TPC

LC Detectors, Jim Brau, Fermilab, April 5, 2002
Synchrotron radiation photons from beam halo in the final doublet halo limited by collimation system
Detector Requirements

Vertex Detector
physics motivates excellent efficiency and purity
large pair background from beamstrahlung
→ large solenoidal field ($\geq 3$ Tesla)
pixelated detector $[(20 \mu m)^2 \rightarrow 2500 \text{ pixels/mm}^2]$ 
min. inner radius ($< 1.5$ cm), $\sim 5$ 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 $\rightarrow$ large BR$^2$
Detector Requirements

Tracking
- robust in Linear Collider environment
- isolated particles (e charge, µ momentum)
- charged particle component of jets
  - jet energy flow measurements
- assists vertex detector with heavy quark tagging
- forward tracking (susy and lum measurement)

Muon system
- high efficiency with small backgrounds
- secondary role in calorimetry ("tail catcher")

Particle ID
- dedicated system not needed for primary HE physics goals
- particle ID built into other subsystems (eg. dE/dx in TPC)
Beamline requirements

Beam energy measurement
Need 50-100 MeV (10^{-4}) precision
  SLD WISRD technique is probably adequate (needs work)
  TESLA plans BPM measurement pre-IP (needs work)
Luminosity spectrum
  acolinearity of Bhabhas
  question - can it be extracted from WISRD?
  What about effect of beam disruption

Polarization measurement
  SLD achieved 0.5% - same technique at NLC should give 0.25%
  TESLA plans only before IP (is this okay? NLC bias says no)
  Positron polarization helps dramatically
LC Detectors

Tesla TDR Detector

American High Energy IR
1.) L
   conventional large detector based on the early American L (Sitges/Fermilab LCWS studies)
2.) SD (silicon detector)
   motivated by energy flow measurement

JLC Detector
3 Tesla
LC Detectors

**TESLA TDR**
- “pixel” vertex detector
- silicon/W EM calorimeter (energy-flow)
- 4 T coil
LC Detectors

- TESLA TDR
Resource Book L Detector

5 barrel CCD vertex detector
3 Tesla Solenoid
  outside hadron calorimeter
TPC Central Tracking (52 → 190 cm)
Intermediate Si strips at R=48 cm
Forward Si discs (5 each)
Pb/scintillator EM and Had calorimeter
  EM     40 x 40 mrad$^2$
  Had    80 x 80 mrad$^2$
Muon - 24  5 cm iron plates with gas
  chambers (RPC?)
5 barrel CCD vertex detector
5 Tesla Solenoid
outside hadron calorimeter
Silicon strips or drift (20 $\rightarrow$ 125 cm) 5 layers
Forward Si discs (5 each)
W/silicon EM calorimeter
0.5 cm pads with 0.7 $X_0$ sampling
and Cu or Fe Had calorimeter (4 $\lambda$)
80 x 80 mrad$^2$
Muon - 24 5cm iron plates with gas chambers (RPC?)
## Resource Book HE Detector Comparison

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solenoid</td>
<td>3 T</td>
<td>5 T</td>
</tr>
<tr>
<td>(R(\text{solenoid}))</td>
<td>4.1 m</td>
<td>2.8 m</td>
</tr>
<tr>
<td>(\mathbf{B}R^2) (tracking)</td>
<td>12 m²T</td>
<td>8 m²T</td>
</tr>
<tr>
<td>(R_M) (EM cal)</td>
<td>2.1 cm</td>
<td>1.9 cm</td>
</tr>
<tr>
<td>(\text{trans.seg}R_M)</td>
<td>3.8</td>
<td>0.26</td>
</tr>
<tr>
<td>(R_{\text{max}}) (muons)</td>
<td>645 cm</td>
<td>604 cm</td>
</tr>
</tbody>
</table>
Resource Book P Detector

5 barrel CCD vertex detector
3 Tesla Solenoid
  inside hadron calorimeter
TPC Central Tracking (25 → 150 cm)
Pb/scintillator or Liq. Argon EM
  and Hadronic calorimeter
    EM    30 x 30 mrad$^2$
    Had   80 x 80 mrad$^2$
Muon - 10 10cm iron plates w/ gas chambers (RPC?)
Vertex Detector

same VXD inside all three detectors (L, SD, and P)
670,000,000 pixels  \[20 \times 20 \times 20 \ (\mu m)^3\]
3 \( \mu m \) hit resolution
inner radius = 1.2 cm
5 layer stand-alone tracking
Impact Parameter Resolution

\[ \cos \theta = 0 \]

\[ dR \text{ (cm)} \]

\[ p \text{ (GeV/c)} \]

B. Schumm
Flavor Tagging

![Flavor Tagging Graphs](image)

T. Abe

LC Detectors, Jim Brau, Fermilab, April 5, 2002
# Tracking

<table>
<thead>
<tr>
<th></th>
<th>L (cm)</th>
<th>SD (cm)</th>
<th>P (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Radius</td>
<td>50</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Outer Radius</td>
<td>200</td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td>Layers</td>
<td>144</td>
<td>5</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>TPC</td>
<td>Si drift or $\mu$ strips</td>
<td>TPC</td>
</tr>
<tr>
<td>Fwd Disks</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>double-sided Si</td>
<td>double-sided Si</td>
<td>double-sided Si</td>
</tr>
<tr>
<td>B(Tesla)</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>
Tracking Resolution

B. Schumm

LC Detectors, Jim Brau, Fermilab, April 5, 2002
# Calorimeters

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>SD</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM Tech</td>
<td>Pb/scin</td>
<td>W/Si</td>
<td>Pb/scin</td>
</tr>
<tr>
<td></td>
<td>(4mm/1mm)x40</td>
<td>(2.5mm/gap)x40</td>
<td>(4mm/3mm)x32</td>
</tr>
<tr>
<td>Had Tech</td>
<td>Pb/scin</td>
<td>Cu or Fe/RPC</td>
<td>Pb/scin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(or Pb)</td>
<td>(or Pb)</td>
</tr>
<tr>
<td>Inner Radius</td>
<td>196 cm</td>
<td>127 cm</td>
<td>150 cm</td>
</tr>
<tr>
<td>EM-outer Radius</td>
<td>220 cm</td>
<td>142 cm</td>
<td>185 cm</td>
</tr>
<tr>
<td>HAD-outer Radius</td>
<td>365 cm</td>
<td>245 cm</td>
<td>295 cm</td>
</tr>
<tr>
<td>Solenoid Coil</td>
<td>outside Had</td>
<td>outside Had</td>
<td>between EM/Had</td>
</tr>
<tr>
<td>EM trans.</td>
<td>40 mr</td>
<td>4 mr</td>
<td>30 mr</td>
</tr>
<tr>
<td>seg.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Had trans.</td>
<td>80 mr</td>
<td>80 mr</td>
<td>80 mr</td>
</tr>
<tr>
<td>seg.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Calorimeter Resolution**

**Jet energy resolution**

- **L:** \( \sigma_{EM}/E = (17\%/\sqrt{E}\text{jet}) \oplus (~1\%) \)
- **SD:** \( \sigma_{EM}/E = (15\%/\sqrt{E}\text{jet}) \oplus (~1\%) \)

**Di-jet mass resolution**

- **L:** \( \sigma_{EM}/E = (64\%/\sqrt{E}_Z) \oplus (~1\%) \)
- **SD:** \( \sigma_{EM}/E = (72\%/\sqrt{E}_Z) \oplus (~1\%) \)

\( e^+e^- \rightarrow 2 \text{ jets} \)

- **L:** \( \sigma \text{ jet} = 0.18/\sqrt{E}_\text{jet} \)
- **SD:** \( \sigma \text{ jet} = 0.15/\sqrt{E}_\text{jet} \)

\( e^+e^- \rightarrow ZZ \)

These are idealized studies, and resolutions will be worse.

R. Frey
Muon Detection

Model L

\(24 \times 5\) cm Fe plates + RPCs

\(\sigma_{r\theta} \approx 1\) cm (x 24) \(\sigma_z \approx 1\) cm (x 4)

coverage to \(~ 50\) mrad

Model SD

\(24 \times 5\) cm Fe plates + RPCs

\(\sigma_{r\theta} \approx 1\) cm (x 24) \(\sigma_z \approx 1\) cm (x 4)

coverage to \(~ 50\) mrad

Model P

\(10 \times 10\) cm Fe plates + RPCs

\(\sigma_{r\theta} \approx 1\) cm (x 10) \(\sigma_z \approx 1\) cm (x 2)

coverage to \(~ 50\) mrad
General considerations:
Based on past experience
Contingency = ~ 40%
Designs constrained

HE IR
L  359.0 M$
SD  326.2 M$

LE IR
P  210.0 M$
## NLC Cost Estimates

<table>
<thead>
<tr>
<th>Description</th>
<th>L</th>
<th>SD</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 Vertex</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>1.2 Tracking</td>
<td>34.6</td>
<td>19.7</td>
<td>23.4</td>
</tr>
<tr>
<td>1.3 Calorimeter</td>
<td>48.9</td>
<td>60.2</td>
<td>40.7</td>
</tr>
<tr>
<td>1.3.1 EM</td>
<td>(28.9)</td>
<td>(50.9)</td>
<td>(23.8)</td>
</tr>
<tr>
<td>1.3.2 Had</td>
<td>(19.6)</td>
<td>(8.9)</td>
<td>(16.5)</td>
</tr>
<tr>
<td>1.3.3 Lum</td>
<td>(0.4)</td>
<td>(0.4)</td>
<td>(0.4)</td>
</tr>
<tr>
<td>1.4 Muon</td>
<td>16.0</td>
<td>16.0</td>
<td>8.8</td>
</tr>
<tr>
<td>1.5 DAQ</td>
<td>27.4</td>
<td>52.2</td>
<td>28.4</td>
</tr>
<tr>
<td>1.6 Magnet &amp; supp</td>
<td>110.8</td>
<td>75.6</td>
<td>30.5</td>
</tr>
<tr>
<td>1.7 Installation</td>
<td>7.3</td>
<td>7.4</td>
<td>6.8</td>
</tr>
<tr>
<td>1.8 Management</td>
<td>7.4</td>
<td>7.7</td>
<td>7.4</td>
</tr>
<tr>
<td><strong>SUBTOTAL</strong></td>
<td>256.4</td>
<td>242.8</td>
<td>150.0</td>
</tr>
<tr>
<td>1.9 Contingency</td>
<td>102.6</td>
<td>83.4</td>
<td>60.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>359.0</strong></td>
<td><strong>326.2</strong></td>
<td><strong>210.0</strong></td>
</tr>
</tbody>
</table>
Example Issues

1. What are the physics reasons for wanting exceptional jet energy (mass) resolution? How do signal/backgrounds and sensitivities vary as a function of resolution? Is mass discrimination of W and Z in the dijet decay mode feasible, and necessary?

2. How does energy flow calorimetry resolution depend on such variables as Moliere radius, \( \Delta \theta / \Delta \varphi \) segmentation, depth segmentation, inner radius, B field, number of radiation lengths in tracker, etc.?

3. What benefits arise from very high precision tracking (e.g. silicon strip tracker); what are the limitations imposed by having relatively few samples, by the associated radiation budget? What minimum radius tracker would be feasible?

4. Evaluate the dependence of physics performance on solenoidal field strength and radius.
The R&D Program

- Many topics require work
- The follow few transparencies list many of the issues
- see also
  - the following talks
  - the report from the International R&D committee
energy flow
need detailed simulation
followed by prototype beam test demonstration
further develop physics cases for excellent energy flow
eg. Higgs self-coupling, WW/ZZ at high energy, recon of top and W
for anomalous couplings?, others (SUSY, BR(H>160))

integrate E-flow with flavor tagging
study readout differences for Tesla/NLC
importance of K0/Lambda in energy flow calorimeter
parametrize E-flow for fast simulation
forward tagger requirements
study effect of muons from collimators/beamline
further development of simulation
clustering
tracking in calorimeter
digital calorimeter
study parameter trade-offs (R seg, layers, coil location, transverse seg.)
in terms of general performance parameters
in terms of physics outcome
refine fast-sim parameters from detailed simulation
integrate electronics with silicon detectors in Si/W
reduce silicon detector costs
engineer reduced gaps
mechanical/assembly issues
B = 5 Tesla?
can scintillating tile Ecal compete with Si/W in granularity, etc.?
crystal EM (value/advantages/disadvantages)
barrel/endcap transition (impact and fixes)
refine the understanding of backgrounds
tolerance of trackers to backgrounds
    will large background be a problem for the TPC (field distortions, etc)
    are ionic space charge effects understood?
study pattern recognition for silicon tracker (include vxd)
study alignment and stability of silicon tracker
what momentum resolution is required for physics,
    eg. Higgs recoil, slepton mass endpoint, low and high energy
understand tracker material budget on physics
physics motivation for dE/dx (what is it?)
detailed simulation of track reconstruction, especially for a silicon option,
    complete with backgrounds and realistic inefficiencies
    include CCDs (presumably) in track reconstruction
timing resolution
readout differences between Tesla/NLC time structure
role of intermediate layer
tracking errors in energy flow (study with calorimeter)
forward tracking role with TPC
alignment (esp. with regard to luminosity spectrum measurement)
develop thorough understanding of trade-offs in TPC, silicon options
large volume drift chamber (being developed at KEK)
development of large volume TPC (large European/US collaboration at work)
development of silicon microstrip and silicon drift systems
    (being developed in US & Japan)
study optimal geometry of barrel and forward system
two track resolution requirements (esp. at high energy)
    this impacts calorimetry - how much?
study K0 and Lambda efficiency
impacts calorimetry?
2D vs. 3D silicon tracker
resolve discrepancy in Higgs BR studies
understand degradation of flavor tagging with real physics events compared to monojets (as seen in past studies)
understand requirements for inner radius, and other parameters
what impact on physics
develop hardened CCDs
develop CCD readout, with increased bandwidth
develop very thin CCD layers (eg. stretched)
segmentation requirements (two track resolution)
  500 GeV u,d,s jets
  pixel size

requirements for purity/efficiency vs. momentum on physics channels
understand role in energy flow (work with calorimetry)
detailed simulation
prototype beam tests
mechanical design of muon system
development of detector options, including scintillator and RPCs
The R&D Program

- luminosity spectrum measurement
- beam energy measurement
- polarization measurement
- positron polarization
  - systematics of the Blondel scheme
- veto gamma-gamma very forward system

Beamline, etc.

General

- is calibration running at $Z^0$ peak essential/useful/useless?

Comment

- In general it would be good if more work was done exercising the simulation code that has been put together under the leadership of Norman Graf. Much work has been devoted toward developing a detailed full simulation.
North American Leadership

New leadership of Physics and Detectors Working Group (established by lab directors)

Jim Brau, co-leader
Mark Oreglia, co-leader

Executive Committee
Ed Blucher
Dave Gerdes
Lawrence Gibbons
Dean Karlen
Young-kee Kim
Jeff Richman
Rick van Kooten
North American Leadership

Facilitate the progress of the working groups in developing the plans for the LC experiments

Issues of focus

the variables of the LC - how important to physics?
  time structure
  energy spectrum
  energy reach and expansion, luminosity
  two detectors?
  Positron polarization
  Gamma-gamma
  electron-electron and gamma-electron

advance the understanding of key detector issues
  eg. energy flow calorimetry
  background tolerance
  vertex detector readout
Coming Meetings

• North American
  - June 27-29, UC-Santa Cruz

• Other regions
  - April 12-15, St. Malo, France (DESY/ECFA)
  - July 10-12, Tokyo, Japan (5th ACFA Workshop)

• International
  - August 26-30, Jeju Is., Korea (LCWS 2002)
Conclusions

The goals for the Linear Collider Detectors will push the state-of-the-art in a number of directions.

- eg. finely segmented calorimetry for energy-flow measurement
- pixel vertex detectors (approaching a billion pixel system)
- integrated readout

Many techniques remain to be understood and developed.

see the following talks

Please get involved in your local effort and connect to the North American effort.

come to Santa Cruz, June 27-29