Review of detector concepts for the future linear collider experiment

University of Victoria HEP Seminar
March 7, 2003

Dean Karlen
University of Victoria / TRIUMF
A linear collider detector
Another linear collider detector
Outline

- Review current ideas for the major components of the linear collider detector:
  - vertexing
  - tracking
  - calorimetry

- Update on the R&D activities for tracking underway at the University of Victoria and Carleton University
Vertex detector concepts

General requirements

- several very precise points on tracks near IP:
  - very good b-tagging capability
    - identify multiple b final states, eg. ZHH and ttH
  - good c-tagging capability
    - separate $H \rightarrow cc$ from $H \rightarrow bb$
  - assign tracks to secondary & tertiary vertices
    - vertex charge
  - improved momentum resolution
- minimal material
- background tolerant
- fast readout (for TESLA beam structure)
Vertex detector concepts

General consensus:

- pixel devices in cylindrical layers
  - the power of pixels demonstrated by SLD CCDs
  - small pixel size to avoid confusion from multiple tracks in jets and from background
- 4-5 layers to be able to do stand alone tracking
  - internal alignment
  - track efficiency can be measured
  - 1st layer in very close (~1 cm) matched last
Vertex detector material budget

- Cylindrical designs lead to large material thickness for forward tracks
  - greater importance for forward region: reduce material
- Goal: layer thickness $\sim 0.1\text{-}0.2\% X_0$ or less
  - SLD layer thickness $0.4\% X_0$
- possible solutions:
  - stretch thin devices (ie. support via tension)
    - stretching a membrane more difficult than wire
  - glue thinner devices to stretched medium
    - gluing complications
  - glue thinner devices to rigid structure
Background tolerance

- Large pair background
  - High B field is essential (to allow 1\textsuperscript{st} layer to be close)
  - Background level falls quickly with radius
  - 1\textsuperscript{st} layer $\sim 0.03$ /mm\textsuperscript{2}/BX
    - $\sim0.1\%$ occ. (100 BX)
    - Not a problem
  - 100 krad in 5 year
    - Probably ok for CCD

- Neutron damage
  - $10^9$ 1 MeV n/cm\textsuperscript{2}/year
    - Probably ok for CCD
Vertex detector technology options

- **CCDs**
  - ~ 20 x 20 \(\mu m^2\) pixels -> 800 M pixels
    - SLD: 300 M pixels
  - coordinate precision: 2-5 \(\mu m\)
    - SLD: 4 \(\mu m\)
  - charge sensed at ends of ladders
    - ADC and data sparsification
    - low power consumption (10 W)
  - use column parallel readout
    - increase readout speed ~50MHz
    - bump bonding
  - cryostat for operation at 200 K
    - could be unnecessary with fast readout
Vertex detector technology options

- **CMOS Monolithic Active Pixel Sensors (MAPS)**
  - same pixel size, precision as CCDs
  - charged sensed at each pixel
    - higher power consumption
    - pulse power?
  - R&D required to bring layer thickness down
  - more radiation resistant than CCDs
  - very good SNR
Vertex detector technology options

- **DEPFET**
  - DEPleted Field Effect Transistor
  - pioneered by MPI-Munich
  - low power (avg < 1W)
  - low noise at room temp. (10 e⁻)

  Thinned devices (50 μm)
Vertex detector decisions

- General concept and performance goals are agreed upon
- Specific technology choice:
  - Continue R&D towards full size prototype ladders
    - will take many years to get there
  - If multiple technologies successful, then material budget (or financial budget) could be the deciding factor:
    - include mechanical support, readout, cooling...
Central tracker concepts
Central tracker concepts

General requirements:

- excellent momentum resolution
  \[ \delta(p^{-1}) \approx 5 \times 10^{-5} \text{ GeV}^{-1} \]
  - full tracking system

  - dilepton recoil mass for ZH events
  - end-point measurements for SUSY decay chains

- excellent pattern recognition and 2 track resolution
  - high-energy, high-density jets

- tolerant to high machine backgrounds
Consensus not yet reached on very basic issues:

- Sensitive medium:
  - gas: many coarse measurements along track
  - silicon: a few precise measurements

- 2D or 3D:
  - gas: drift chamber or TPC?
  - silicon: silicon strip or silicon drift?
Central tracking designs

- **Drift chamber**
  - small cell
  - axial/stereo layers
  - 4.6 m long
Central tracking designs

- Time projection chamber
TPC readout technology choices

- **Gas Electron Multiplier (GEM)**
  - negligible E x B distortions: improved resolution
  - narrower and faster signals: improved 2 particle separation
  - reduced ion feedback
TPC readout technology choices

- Micromegas:
  - same advantages as GEM
  - more robust
Central tracking designs

- Silicon drift or microstrip detectors
Central tracking technology options

- Silicon drift or microstrip detectors
  - thinned detectors (200 µm)
  - short vs long strips
  - mechanical support
  - pulsed power

- SiLC collaboration has formed
Pattern recognition: gas vs. Si

- Human pattern recognition much prefers figure on left, even if points on right are more precise.
- Is 5 layers enough for computer pattern recognition?
Central tracking technology decision

To make a well informed choice for the optimal tracking detector technology requires:

- demonstrated performance in large scale prototypes in cosmic ray and test beams studies (with B field)
- detailed simulations of realistic detectors
- well tuned pattern recognition and track fitting programs
- comparison of performance for several key physics measurements with machine backgrounds

- if no clear winner: conservative choice will have lead
Calorimeter concepts
Calorimeter concepts

- General requirements
  - Hermetic
  - Excellent energy resolution for jets
  - Excellent angular resolution
  - Ability to reconstruct non-pointing photons
  - Good time resolution

- Biggest issue driving calorimeter design:

Jet energy resolution
**Jet Energy Resolution Requirements**

- **Goal:** distinguish W and Z in their hadronic modes
  - requires: jet energy resolution, $\sigma_E \approx 30\% \sqrt{E}$
  - example: $e^+ e^- \rightarrow WW \nu \bar{\nu}$, $e^+ e^- \rightarrow ZZ \nu \bar{\nu}$

---

![Graphs showing jet energy resolution comparison](image)

Other studies indicate resolution degradation from 60% $\sqrt{E}$ to 30% $\sqrt{E}$ is equivalent to about 40% reduction in luminosity.
When kinematic fits are not possible, Energy Flow Algorithms give the best jet energy resolution:

- Use tracking detectors to measure energy of charged particles (65% of the typical jet energy)
- EM calorimeter for photons (25%)
- EM and Had calorimeter for neutral hadrons (10%)

\[
E_{\text{jet}} = E_{\text{charged}} + E_{\text{photons}} + E_{\text{neut. had.}}
\]

\[
\sigma^2_{E_{\text{jet}}} = \sigma^2_{E_{\text{charged}}} + \sigma^2_{E_{\text{photons}}} + \sigma^2_{E_{\text{neut. had.}}} + \sigma^2_{\text{confusion}}
\]
Energy Flow Algorithms

\[ E_{\text{jet}} = E_{\text{charged}} + E_{\text{photons}} + E_{\text{neut. had.}} \]
\[ \sigma_{E_{\text{jet}}}^2 = \sigma_{E_{\text{charged}}}^2 + \sigma_{E_{\text{photons}}}^2 + \sigma_{E_{\text{neut. had.}}}^2 + \sigma_{\text{confusion}}^2 \]

Assume:

\[ \sigma_{E_{\text{charged}}}^2 \approx \left(5 \times 10^{-5}\right)^2 \sum \frac{E_{\text{charged}}^4}{\text{GeV}^2} \approx (0.02 \text{ GeV})^2 \frac{1}{10} \sum \left(\frac{E_{\text{charged}}}{10 \text{ GeV}}\right)^4 \]

\[ \sigma_{E_{\text{photons}}}^2 \approx (0.11)^2 \sum \left( E_{\text{photon}} \cdot \text{GeV} \right) \approx (0.6 \text{ GeV})^2 \frac{E_{\text{jet}}}{100 \text{ GeV}} \]

\[ \sigma_{E_{\text{neut. had.}}}^2 \approx (0.40)^2 \sum \left( E_{\text{neut. had.}} \cdot \text{GeV} \right) \approx (1.3 \text{ GeV})^2 \frac{E_{\text{jet}}}{100 \text{ GeV}} \]
Energy Flow Algorithms

\[ E_{\text{jet}} = E_{\text{charged}} + E_{\text{photons}} + E_{\text{neut. had.}} \]

\[ \sigma^2_{E_{\text{jet}}} = \sigma^2_{E_{\text{charged}}} + \sigma^2_{E_{\text{photons}}} + \sigma^2_{E_{\text{neut. had.}}} + \sigma^2_{\text{confusion}} \]

- Ignoring the (typically) negligible tracking term:

\[ \sigma^2_{E_{\text{jet}}} \approx (0.14)^2 (E_{\text{jet}} \cdot \text{GeV}) + \sigma^2_{\text{confusion}} \approx (0.3)^2 (E_{\text{jet}} \cdot \text{GeV}) \]

\[ \sigma^2_{\text{confusion}} \text{ is the largest term of all} \]
Energy Flow Algorithms

To reduce confusion in the calorimeters:
- Have large B field and large calorimeter inner radius
  - to separate the particles
- Use materials with small Moliere radius
  - to reduce shower overlap
- Finely segment calorimeters (in 3D)
  - to allow separation of neighbouring showers
- Place calorimeters inside coil, no cracks
- Develop smart algorithms
Moliere radius (Iron vs. Tungsten)

(many images courtesy H. Videau)

7 March 2003  Dean Karlen / Review of Detector Concepts
Density of showers and granularity

W dijet impact on the first 4 $X^0$ of the calorimeter in $\theta \phi$ projection

The image is 100 x 100 mrad

X generated $\gamma$'s 8
+ charged 4
* neutral had. 1
O reconstructed $\gamma$'s

proposed granularity $\sim 10 \times 10 \text{ mm}^2$
Calorimeter design concepts
Highest granularity designs: Si/W ECAL

- Moliere radius for Tungsten: \( r_w = 9 \text{ mm} \)
  - gaps increase this: \( r_m = r_w \left( 1 + \frac{R_{gap}}{R_w} \right) \)
  - \( R_w = 2 - 3 \text{ mm} \) (2.5 mm = 0.7 \( X_0 \))
  - \( \Rightarrow \) gaps for readout need to be \( \sim 2.5 \text{ mm} \) or less

2.8 mm readout gap
Si/W ECAL: Si

- Total amount of Si required: $1-3 \times 10^3 \, m^2$

DATA From H.F-W. Sadrozinski, UC-Santa Cruz
Cost evolution for Si microstrip detectors:

Si/W ECAL costs dominated by Si cost: will it become affordable?

Blank wafer price 6"

Used in the TDR

DATA From H.F-W. Sadrozinski, UC-Santa Cruz

2 $/cm²
High granularity HCAL

- For best jet energy measurements, energy flow algorithms need fine segmentation in the hadron calorimeter too.

- Digital HCAL:
  - transverse segmentation approx. $X_0$:
    - 4 mm (W)
    - 18 mm (Fe)
  - many layers (3D)
Digital HCAL readout

- reduced cost: (Digital = “1 bit ADC”)
- several technology choices
  - resistive plate chambers
  - gas electron multipliers
  - scintillator
Highly segmented calorimeter R&D

- R&D not segmented: CALICE collaboration
  - about 130 members from all regions
  - goal: to build ~ 1 m³ prototype for beam test in 2004

RPC prototype testing at ANL
Alternative calorimeter designs

- Arguments in favour of a highly segmented calorimeter are quite compelling...
  ... but there is not yet complete consensus on this issue

- Other calorimeter technologies under consideration include:
  - lead / scintillator tile
  - crystal
  - Sashlick
Calorimetry decisions

- Consensus not yet reached on design
  - effort on EFA optimized designs growing
  - strong case needs to be made for the large cost increment

- Need:
  - further simulation
  - test beam R&D to verify simulation
  - clever algorithms
  - head to head comparison of performance in key physics measurements for the different technologies
LC Tracking R&D in Canada
LC Tracking R&D in Canada

- A large group involved:
  - Victoria: D.K., Gabe Rosenbaum, Paul Poffenburger
  - Carleton: Bob Carnegie, Madhu Dixit, Hans Mes, Kirsten Sachs
  - U. Montreal: J.-P. Martin

- Area of focus:
  - optimizing the readout scheme for a time projection chamber central tracker
    - Gas Electron Multipliers
    - Micromegas detectors
GEM TPC

- Advantages for GEM:
  - negligible $E \times B$ distortions
    - improved resolution
  - narrower and faster signals
    - improved 2 particle separation
  - reduced ion feedback
    - gating not needed (?)

- Problem:
  - narrower signal pattern require smaller pads ($$) or defocussing mechanism to achieve optimal resolution
    - DESY: chevrons, Carleton: induction, Victoria: gas
Track Fitting in a GEM TPC

- x-y track fit uses a linear Gaussian model for the ionization cloud
  - i.e. no fluctuations

- three parameter fit:
  - $x_0$ (x at y=0)
  - $\phi$ (azimuthal angle)
  - $\sigma$ (transverse s.d. of cloud)

- maximize the likelihood of the observed charge fractions from each row

Mathematical formulation:

$$l(b,\phi,\sigma,h,w) = \int_{-w/2}^{w/2} \int_{-h/2}^{h/2} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{[(x-x_0)\cos\phi + y\sin\phi]^2}{2\sigma^2}}$$

$$= \eta(b,\phi,\sigma,h,w) - \eta(b,\phi,\sigma,-h,w) + \eta(b,\phi,\sigma,-h,-w) - \eta(b,\phi,\sigma,h,-w)$$

$$\eta(b,\phi,\sigma,h,w) = \frac{1}{\cos\phi\sin\phi} \xi(b + \frac{w}{2}\cos\phi + \frac{h}{2}\sin\phi,\sigma)$$

$$\xi(u,\sigma) = \frac{u}{2} \text{erf} \left( \frac{u}{\sqrt{2}\sigma} \right) + \frac{\sigma}{\sqrt{2\pi}} \exp \left( -\frac{u^2}{2\sigma^2} \right)$$
GEM TPC

Naïve calculation for optimum resolution:

\[ \delta x = \frac{\sigma_D \sqrt{\ell [\text{cm}]}}{\sqrt{N_{\text{primary}}}} = \frac{27 \mu m \sqrt{200}}{\sqrt{30 \text{ mm} \times 9 \text{ e} / \text{mm}}} = 23 \mu m \]
GEM TPC

Ar CF$_4$ (98:2): 5 rows of 2 mm x 6 mm pads

$\chi^2$ resolution (microns)

Drift length (cm)

- standard row layout
- chevron 2
- chevron 4
- chevron 10
- optimum (naive)

Chevrons unnecessary in Ar CF$_4$

GEM TPC

7 March 2003

Dean Karlen / Review of Detector Concepts
Comparison of Pad Widths

50 cm drift: corresponds to transverse cloud s.d. of 0.58 mm
Reality Check: TPC prototypes

- Outer 6 rows are used to define track parameters
  - inner two rows: resolution studies (fit for $x_0$ alone)
  - 2 mm x 6 mm / 3 mm x 5 mm

Carleton TPC
Example: for Ar CO$_2$ (90:10)

- $d < 2$ cm
- $|\phi| < 0.1$ rad

- pad width: 2 mm
- $\langle \sigma \rangle = 0.5$ mm
- $w/\langle \sigma \rangle = 4$

resolution: 140 $\mu$m
Resolution vs. Drift Distance

Ar CO₂

|φ| < 0.1

3 mm x 5 mm pads

2 mm x 6 mm pads

Naïve optimum:
- all primaries collected
- upper: $\sigma_0$ before amp.
- lower: $\sigma_0$ after amp.

MC simulations:
- GEM efficiencies:
  - collection 1.0
  - extraction 0.7
Magnetic field tests

- Victoria TPC is being commissioned in room 022
  - designed for TRIUMF & DESY magnet tests
Design of drift volume
Drift cell completed

![Drift cell image]

7 March 2003

Dean Karlen / Review of Detector Concepts
Pad layout

2mm x 7mm pads
Pad signals: P10 gas

![Graph showing Pad signals and Cosmic trigger](image_url)
30 cm drift
Cosmic data taken last week:
- use e-scope features to make mini-DAQ system
- cut on amplitude and time difference of outer pads
Plans for Victoria TPC work

- Incorporate the STAR electronics to readout all 256 pads
  - cosmic data taking
  - tracking resolution studies
  - optimization of operating conditions

- Operate TPC in magnetic fields
  - 1 Tesla at TRIUMF
  - 5 Tesla at DESY
Conclusions

- The general concepts for a linear collider detector are now well established
  - some choices still to be made

- Significant effort is continuing in detector R&D:
  - refining the ideas
  - proving the validity of specific designs
  - developing alternative concepts

- This work is essential now, in order to be able to make the right decisions in the (near) future