Charged Particle Tracking Issues for a Linear Collider Detector

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Conventional Wisdom:

“Easy” to build linear collider detector (e.g., clone SLD or a LEP detector)

• Statement more or less true, but maximizing physics output argues for more aggressive approach

• Will discuss here how to be more aggressive in tracking charged particles
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Physics Drivers (a sampling)

Good primary / secondary vertex reconstruction (b vs c):
• $B(H\rightarrow cc)$ [distinguish SM from SUSY Higgs]
• Charm-tag $W^+W^-$ final states [strong coupling]

Good momentum resolution: [ $\delta(1/pt) \sim 5 \times 10^{-5} \text{ GeV}^{-1}$ ]
• Clean Higgs signal from dilepton recoil mass
• End-point mass spectra in SUSY cascades

Good pattern recognition / 2-track separation
• Jet energies in $W^+W^-$ final states (Energy-flow algorithm)
Physics Drivers (a sampling)

Good forward tracking \([ |\cos(\theta)| \to 0.99 ]\)
[\(\delta \theta \sim 10^{-5} \text{ rad} ; \delta(1/pt) \sim 2 \times 10^{-4} \text{ GeV}^{-1} \)]

- New t-channel processes (e.g., chargino production)
- Differential luminosity measurement
  (scanning top-pair threshold lineshape)

LEP/SLC detectors not useless for these measurements,
but one would like to do them very well
What tracker designs have been studied?

Asia:
- CCD vertex detector
- Large-volume drift chamber (DC)

Europe:
- CCD, CMOS or hybrid pixel vertex detector
- Large-volume time projection chamber (TPC)
- Forward active pixel and silicon microstrip disks, straw chamber behind TPC endcap

North America:
- CCD vertex detector
- Large-volume TPC or large-radius silicon tracker (drift / microstrip)
- Forward silicon microstrip disks
Vertex detector baseline
(Europe & North America)
Central tracker LD baseline (North America)
Central tracker SD baseline (North America)
Expected Impact Parameter Resolutions (vs $p$)

\[ \cos\theta = 0 \]

\[ dR (\mu m) \]

\[ p \ (GeV/c) \]

- $L$
- $SD$
- $P$
Resulting b/c tagging performance (Xella-Hansen – RAL/LCFI)

Efficiencies vs Purities at 91 GeV

- Tagging of b jets has purity > 90% for efficiency up to 80%
- Performance very good and very similar to SLD

- Tagging of c jets has purity > 80% for efficiency up to 40%
- Significant (factor 2-3) improvement over SLD performance
- Excellent c discrimination when b is the only background

Prospect for tagging new physics processes are good
Expected Momentum Resolutions (vs p)

\[ \cos \theta = 0 \]

\[ \frac{\delta p_t}{p_t} \]

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

\[ 1 \quad 5 \quad 10 \quad 50 \quad 100 \quad 500 \quad 1000 \]
Expected Momentum Resolutions (vs \(\cos \theta\))
Technical Issues

Radius of innermost layer of vertex detector:

- Fierce background from Bethe-Heitler pairs (see figure)
  - Drives B-field magnitude
  - Pushes tolerance on background calculations

- Neutron backgrounds drive required rad-hardness
Pair Background
(plot from T. Markiewicz)
Technical Issues

Tracker material

• Make vertex detector layers as thin as possible to reduce degradation of impact parameter resolution – Probably important

• Minimize material in central tracker too to reduce degradation of momentum resolution – Desirable, but perhaps not critical

• Reduce secondary backgrounds from machine
Technical Issues

Pattern recognition – Vertex Detector

• Want pixellated vertex detector

(CCDD vs Active (monolithic/hybrid) Pixels):
  – Reconstruct primary / secondary vertices accurately
  – Provide “seed” tracks for central / forward trackers

• CCD’s provide superior spatial resolution, but readout time a problem with Tesla bunch train and expected backgrounds.

• Active pixels fast and radiation-hard, but thick & coarse.
Technical Issues

Pattern recognition – Central Tracker

- 3-D vs 2-D technologies:
  - Gas: TPC vs DC
  - Silicon: Drift vs Microstrips
  - 3-D eases reconstruction and improves robustness against backgrounds (SR photons, $\gamma\gamma \rightarrow$ jets). May come at higher cost.
- Few precise hits (silicon) vs many coarse hits (gas)
  - Effect on 2-track separation? $\rightarrow$ Energy flow
  - Reconstruct long-lived decays?
  - Cope with large machine backgrounds?
  - Pointing to shower max in calorimeter $\rightarrow$ Energy flow
- Does pixel vertex detector provide enough “stand-alone” tracking (seeding) to make above choices non-critical?
Technical Issues

Intermediate Tracker (needed for gas trackers?)

- Depending on $R_{\text{max}}$ of $V_{\text{det}}$ and $R_{\text{min}}$ of central tracker, a precise silicon layer at gas chamber $R_{\text{min}}$ improves $\delta p$ by up to factor of two
- Might help pattern recognition (might hurt!)
- Offers possible bunch tagging via precise timing to disentangle two-photon crud, machine backgrounds (e.g., scintillating fiber)
Technical Issues

What about $dE/dx$?

- Capability “comes for free” in gas chambers, but electronics to exploit it is not free
- Some capability possible with silicon, but useful mainly for tagging very heavy (exotic) particles
- Do we need it?
  - Identifying high-energy electrons will be easy, anyway.
  - Do we care enough about $K/\pi$ separation to let $dE/dx$ influence tracker design choice?
Technical Issues

Mechanical / electronic ramifications of thin silicon

• Ultra-thin CCD’s can be “stretched” to maintain rigidity without support structure
  – Mechanical challenge

• Silicon microstrip ladders can be built long to get front-end electronics out of fiducial volume.
  – Affects shaping time of electronics, could be a problem in high-background environment
How do we make choices?

We need:

• Simulations, Simulations, Simulations! (fast and full Monte Carlo)
• Detector R&D to ground simulations in reality.

Will present:

• My (abbreviated) tracking simulations wish list
  Note: much work already underway & reported
• Overview of ongoing tracking detector R&D
A Tracking Simulations Wish List

Fast Monte Carlo:

- Where do we reach diminishing returns on impact parameter resolution in measuring Higgs charm vs bottom branching ratios? How thin do pixel layers really need to be?

- Where do we reach diminishing returns on momentum resolution in measuring Higgs recoil mass and slepton mass end-point spectra, taking into account particle decay widths, initial state radiation, and beam energy spread?
Studies of performance – A. Chou (SLAC)
(comparing extremes in resolution/material)
Studies of performance – H. Yang (U. Michigan)
(Raw dilepton recoil mass in Higgsstrahlung)
(Resulting precision on fitted Higgs mass – no beam energy spread)
A Tracking Simulations Wish List

**Fast Monte Carlo:**

- Compelling 500 GeV physics example where material budget in central tracker matters:
  - What $\Delta p/p$ do we need at 1 GeV? ($10^{-2}$, $10^{-3}$, $10^{-4}$)?
  - What photon conversion rate is unacceptable? (10%)?

- Compelling 500 GeV physics example where $dE/dx$ buys us much.
A Tracking Simulations Wish List

**Full Monte Carlo:**

- Robust, reasonably optimized track reconstruction for North American LD and SD baseline designs, including:
  - Non-cheat reconstruction from hits in Si barrel microstrip option
  - Non-cheat reconstruction from hits in Si forward disk microstrips
  - Self-contained vertex detector tracking with extrapolation outward

- Comparison of energy flow performance among the 3-D, 2-D, silicon, gaseous options
  (e.g., WW vs ZZ all-hadronic final states, overlaps with calorimeter wish list!)
Present status of full track reconstruction – work needed
(fast/full MC comparison by H. Yang)
A Tracking Simulations Wish List

Full Monte Carlo:

- Realistic study of benefits arising in LD design from:
  - Intermediate silicon layer just inside the TPC (pat. rec., $\delta p/p$)
  - Intermediate sci-fiber layer in same place (timing)
  - Outer “z” (straw/silicon) layer (pointing into calorimeter)
  - Outer endcap (straw/silicon) layer (better $\delta p/p$ at low $\theta$)

(“realism” includes, e.g., systematic alignment errors, backgrounds from multiple bunches, and calorimeter backsplash)
A Tracking Simulations Wish List

**Full** Monte Carlo:

- TPC E-field distortion by ionic space charge
  - Proponents confident that new readout schemes (GEM, MicroMEGAS) and gating grid adequately suppress avalanche ion feedback
  - Primary ionization said to be okay too for expected machine backgrounds
  - What if backgrounds are much worse? (need really full Monte Carlo to study!)
A Tracking Simulations Wish List

**Full** Monte Carlo:

- Wire saturation in drift chamber from larger-than-expected accelerator backgrounds:
  - Synchrotron radiation background (1 MeV Compton curlers)
  - Muons from beam halo hitting collimators
Ongoing or Planned R&D for Vertex Detector (overview)

- CCD’s
  - Europe, North America, Asia

- Hybrid, Monolithic, & DEPFET Pixels
  - Europe
Ongoing or Planned CCD R&D

• **Minimizing material:** (JLC, LCFI*, Oregon, Yale)
  - Thinner silicon
  - Stretched silicon
  - Room-temperature operation

• **Coping with radiation** (JLC, LCFI, Oregon, Yale)
  - Manufacture of harder detectors
  - Techniques for reducing / coping with damage (charge injection, lower temperature)

• **Speed up readout** (LCFI, Oregon, Yale)
  - Higher clock speed
  - Parallel column readout
  - Integration

*LCFI Collaboration: Bristol, Glasgow, Lancaster, Liverpool, Oxford, RAL
Stretched CCD’s (LCFI collab)
Coping with neutron radiation
– N. Sinev (U. Oregon)

Image of damaged sites

$T = 187K$, after dose of $2 \times 10^9 \text{n/cm}^2$

Image of damaged sites after flushing with light

$T = 187K$, dose $2 \times 10^9 \text{n/cm}^2$, cleaning charge
Column Parallel Readout (LCFI collab)
Ongoing or Planned Hybrid Pixel R&D
(CERN, Helsinki, INFN, Krakow, Warsaw)

- Reducing total thickness

- Improving spatial resolution
  - Smaller pitch
  - Interleaved sensors exploiting capacitive induction
Ongoing or Planned CMOS Pixel R&D
(also known as MAPS = Monolithic Active Pixel Sensor)
(Strasbourg)

• Development (!)

• Larger wafers

• Thinner substrate

• More integrated readout
Prototype MAPS chips (MIMOSA I and II)
Ongoing or Planned DEPFET* Pixel R&D

(MPI)

- Development (!)
- Thinner layer and readout
- Thinner, integrated readout
- Improving spatial resolution (smaller pitch)

*Similar to MAPS but with high-resistivity silicon, FET in readout chain, readout from sides (for now)
DEPFET Principle of Operation

(a) Sideward depletion

(b) p⁺ diode => p-channel transistor

(c) Full depletion
Potential minimum is shifted towards the transistor channel
Ongoing or Planned R&D for Central Trackers (overview)

• Time Projection Chamber
  – Mostly Europe, some Canada, U.S.
  – Concrete design, R&D focused, funded

• Drift chamber
  – Mostly Japan
  – Concrete design, R&D well focused, funded

• Silicon (drift & microstrip)
  – Mostly U.S.
  – Competing designs, R&D strapped for funds
Ongoing or Planned TPC R&D

• **Readout scheme** *(Aachen, Carleton, DESY, Karlsruhe, LBNL, MIT, MPI, NIKHEF, Novosibirsk, Orsay, Saclay)*
  - Optimizing spatial resolution for given electronics channel count
  - GEM vs MicroMEGAS vs wires
  - Suppressing ion feedback (e.g., multi-GEMS, gating grid)

• **Readout pad shape** *(Aachen, Carleton, DESY, LBNL, MPI)*
  - Affects channel count, intrinsic spatial resolution, 2-track resolution, and dE/dx resolution
  - Chevrons (clever splitting/ganging) vs induction

• **Gas mixture** *(DESY, Krakow, MIT, Saclay, Novosibirsk, MPI)*
  - Drift velocity (resolution vs fast clearing)
  - Quenching with hydrocarbons vs reducing neutron backgrounds
  - Aging
  - Affects field cage design
R&D Work at Carleton University (D. Karlen)

(nice example of university-scale R&D project)
Charge sharing studies for hexagonal pads

2D Gaussian model
Results on localization from charge sharing – P10

\[
\bar{x} = 0.408 \text{ mm} \\
\sigma_x = 0.066 \text{ mm}
\]

\[
(x,y)_{\text{col}} = (0.4, 1.243) \text{ mm}
\]

\[
\bar{y} = 1.265 \text{ mm} \\
\sigma_y = 0.064 \text{ mm}
\]
Tracking studies with staggered rectangular pads

- Cosmic ray telescope
- Readout pad layout
Alternative pad layout: Chevrons
Alternative Readout: MicroMEGAS

MICROMEGAS
PRINCIPLE & OPERATION

IONIZING PARTICLE
Drift Electrode
Drift space

Conversion Gap 3.2mm
LOW FIELD 1kV/cm

IONISATION PROCESS

Amplification Gap 100μm
HIGH FIELD 40kV/cm

AVALANCHE PROCESS

Printed Circuit Board
polymide spacer
Readout Electronics
Readout Signal
Ongoing or Planned TPC R&D

- **Electronics** *(Carleton, LBNL, NIKHEF, MPI)*
  - Need $O(10^6)$ pads to exploit intrinsic x-y TPC granularity
  - Need high-speed sampling (~100 MHz) to exploit intrinsic granularity and dE/dx

- **Mechanics** *(LBNL, MPI)*
  - Minimize material in inner/outer field cages, endplates
  - Eliminating wire readout helps!
  - But high-speed sampling may require cooling, despite low duty cycle

- **Calibration** *(LBNL, NIKHEF, MPI)*
  - Laser system?
  - “Z” chamber at outer radius?

- **Simulation** *(Aachen, Carleton, DESY, NIKHEF)*
  - Readout scheme modelling for design optimization
  - Optimizing pad size & shape
Ongoing or Planned Drift Chamber R&D (KEK)

- Controlling/monitoring wire sag over 4.6 meters
- Uniform spatial resolution (85 microns) over chamber volume
- Good 2-track resolution (<2 mm)
- Stable operation of stereo cells
- Gas gain saturation (affects dE/dx, 2-track resol)
- Lorentz angle effect on cell design
- Wire tension relaxation (Al)
- Optimizing gas mixture
- Neutron backgrounds (planned)
JLC Central Drift Chamber (KEK)

Super-layer layout:

Cell geometry:
Ongoing or Planned Silicon R&D

• Thinner silicon strips (LPNHE-Paris, Santa Cruz, SLAC)
  – Reduce material of tracker
  – Presents support / stabilization challenge

• Short vs long strips (LPNHE-Paris, Santa Cruz, SLAC)
  – Short gives timing precision but more FEE in fiducial volume
  – Long minimizes material, reduces noise, but sacrifices timing
  – Choice dependent on expected backgrounds
Ongoing or Planned Silicon R&D

- **Barrel/disks support structure** (LPNHE-Paris, Santa Cruz, SLAC, Wayne State)
  - Want low-mass, stiff support
  - ATLAS alignment scheme reduces stiffness demands

- **Power-switching μstrip readout chip** (LPNHE-Paris, Santa Cruz, SLAC)
  - Exploiting low duty cycle of collider
  - Reduce cooling infrastructure material
  - Stability?
Ongoing or Planned Silicon R&D

• Other strip readout issues (LPNHE-Paris, Santa Cruz, SLAC)
  – Lorentz angle in high B-field
  – p-side readout for “stereo”?
  – Time-walk compensation, dE/dx measurement?
  – More electronics integration

• Specific Silicon Drift Detector Issues (Wayne State)
  – Improve spatial resolution to <10 microns (x-y, r-z)
  – Increase drift length
  – Low-mass readout for FEE in fiducial volume
To learn more about many of these simulation and R&D issues, see parallel-session transparencies from Chicago Linear Collider Workshop at

http://LCworkshop.uchicago.edu/

See also the pre-Snowmass efforts in North American Vertexing & Tracking studies at the working group web pages:

http://blueox.uoregon.edu/~jimbrau/LC/lcvtxdet.html

http://www-mhp.physics.lsa.umich.edu/~keithr/LC/trkmain.html

And talks given at Snowmass in E3 sessions:

http://battagl.home.cern.ch/~battagl/snowmass2001/WG_Schedule.html
Summary:

• Much work to be done in detector design optimization at simulations level, especially for central and forward tracking
• Solid vertex detector baseline technology – CCD, but interesting alternatives under rapid development in Europe
• Technology choice for central tracker still very much up in the air, but TPC and DC options have received most study
• Readout technology for TPC option still wide open
• Silicon central tracking options (microstrip or drift) need much more R&D attention

(new Silicon Linear Collider collaboration now getting started – see http://scipp.ucsc.edu/~schumm/SILC)

Help is needed and welcome!