Physics Opportunities of the Linear Collider

- Premier physics goals of linear collider characterized by heavy-quark decays and small cross sections
  - eg.
    - Higgs branching ratios
    - $t\bar{t}$ (usually 6 jets, 2 b)
    - $t\bar{t}h$ (usually 8 jets, 4 b jets)
    - $AH$ (12 jets with 4 b jets)
    - and other reactions
Requirements of the Vertex Detector

• Highly efficient and pure b and c tagging, including tertiary vertices (b→c)

• Charge tagging (eg. b/b discrimination)

• These goals are achieved by optimized impact parameter performance:
  – point resolution < 4 μm
  – detector thickness < 0.2% X₀
  – inner radius < 2 - 3 cm
  – good central tracker linking

• Also must take care with timing and radiation hardness
SLD has demonstrated the power of a **PIXEL** detector in the LC environment

- 307,000,000 pixels
- 3.8 μm point resolution
- pure and efficient flavor tagging at the Z-pole
  - ~ 60% b eff with 98% purity
  - > 20% c eff with ~ 60% purity

- We need a **pixel** solution
  - decision on option can wait
  - optimize options based on active R&D program
The SLD Vertex Detectors

**VXD2**  
Proc 26th Int Conf on HEP, Dallas TX (1992)

**VXD3**  
NIM A400 (1997) 287
Options under development

- **CCDs**
  - system level demonstration with SLD (307,000,000 pixels)
  - R&D to advance performance

- **Hybrid Active Pixels (HAPDs)**
  - fast, rad-hard

- **Monolithic APDs**
  - fast, rad-hard

We need to pursue all of these options vigorously to ensure the best possible vertex detection at the LC.
Session D3

- **CCDs**
  - C. Damerell (system development)
  - K. Stefanov (mech./ rad-hard devel.)

- **Hybrid APDs**
  - M. Caccia (prototype, charge sharing)
  - G. Alimonti (“3-D” detectors, bmp bnd)

- **Monolithic APDs**
  - G. Deptuch (prototype, beam test)

- **Performance studies**
  - T. Abe (heavy jet tagging)
  - J. Brau (Higgs BRs)
  - S. Xella (flavor tagging)
  - B. Schumm (aggressive scenarios)
  - M. Battaglia (3 Tev - CLIC)
  - A. Miyamoto (flavor tagging)
D3: Vertex Detectors

Charge Coupled Devices
(CCDs)

• Chris Damerell
  – system development
    • build on SLD experience with years of operation with 307,000,000 pixels
  – 5 barrel, 799,000,000 pixels with beampipe radius of 14 mm and 3 hit coverage to $\cos \theta = 0.96$
  – thinning ladders to 0.06% $X_0$
  – Readout architecture
    • column-parallel readout for TESLA

• Konstantine Stefanov
  – investigating near $T_{room}$ use
  – mechanical design studies
  – rad-hard devel. to reduce CTI
    • improves 60-100 times
    • “will survive 10 years”
• Currently pushing the ‘unsupported silicon’ option

• Results with thin glass CCD models are most encouraging

• Assisted by the strong technology evolving for PTPs (paper-thin packages)
NLC: \[190 \times 120 = 22.8 \times 10^3\] bunches/s

TESLA: \[2820 \times 5 = 14.1 \times 10^3\] bunches/s

Luminosity and background per bunch are similar.

NLC: CCD readout in 8 ms between bunch trains provides adequate background control

TESLA: 15 times more luminosity per train, so need to read repeatedly during each train of 950 \(\mu s\)

→ Concept of column-parallel readout in 50 \(\mu s\), which is interesting for other CCD application areas.

[An earlier option of fast clear, fast trigger and kicker magnet to kill the bgd was excluded by GMSB and other subtle signatures: the LC DAQ must run in an untriggered mode.]
Notch CCD

- Additional implant in the channel;
- 'Notch' in the potential profile;
- Small signal packets are transported in the notch;
- $\text{CTI} \propto \frac{n_t}{n_s}$,

$n_t$ - concentration of defects,

$n_s$ - concentration of signal electrons.

Signal density for small charge packets increases

Lower CTI
Hamamatsu Photonics Notch CCD has 3 μm wide additional implant in the channel.

Electron irradiation:
- Vertical (parallel) CTI is about 3 times lower than that in a conventional CCD.

Neutron irradiation:
- Vertical CTI of CCD, irradiated to $5.7 \times 10^9$ neutrons/cm² is less than $5 \times 10^{-5}$. 
Injection of additional charge (fat zero effect)

- Dark current electrons occupy traps
- Less signal electrons are lost
- The most powerful method for reducing charge losses
  - Injection of 1000 electrons introduces 32 electrons (RMS) noise
  - Noise of high speed CCD: about 100 electrons (RMS)
  - Requires CCD with an injection structure

Experiment on EEV02-06 CCD: 8 to 10 times CTI reduction
CTI improvements

After 10 years of operation (≈5×10^{12} \text{ electrons/cm}^2 \text{ } ^{90}\text{Sr}, \text{ and } \approx5\times10^9 \text{ neutrons/cm}^2 \text{ } ^{252}\text{Cf})

- Vertical CTI reaches 4.8×10^{-2} (at maximum, 250 kpix/s)
- Horizontal CTI is much smaller than the VCTI.
- Neutron irradiation causes small CTI.

Budget for improvement:

<table>
<thead>
<tr>
<th>Option</th>
<th>VCTI improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raise the readout speed to &gt; 5 Mpix/s</td>
<td>≈1.3 times</td>
</tr>
<tr>
<td>Use 2-phase CCD</td>
<td>≈2.5 times</td>
</tr>
<tr>
<td>Use notch CCD</td>
<td>3 to 4 times</td>
</tr>
<tr>
<td>Inject dark charge ≈1000 electrons (at &gt;5 °C)</td>
<td>6 to 8 times</td>
</tr>
<tr>
<td>Total improvement</td>
<td>≈ 60 to 100 times</td>
</tr>
</tbody>
</table>

Recent simulation gives 1.5×10^{12} \text{ e}^+\text{e}^- \text{ pairs/cm}^2/10 \text{ years}, however their energy is higher than \text{ } ^{90}\text{Sr} electrons (safety margin of 10 gives 15×10^{12} \text{ electrons/cm}^2 \text{ } ^{90}\text{Sr}).
Model CCD

Based on the present knowledge on radiation damage effects and device architecture

Reduced worst-case CTI:

Vertical CTI to $\approx 8 \times 10^{-4}$, output charge after 250 transfers: $(1 - 8 \times 10^{-4})^{250} = 0.82$ (18% loss)

Horizontal CTI to $\approx 8 \times 10^{-5}$, output charge after 1000 transfers: $(1 - 8 \times 10^{-5})^{1000} = 0.92$ (8% loss)

Total charge at the output: $0.82 \times 0.92 = 0.75$ (25% loss)

The CCD will survive for 10 years ($\approx 5 \times 10^{12}$ electrons/cm$^2$ $^{90}$Sr, $\approx 5 \times 10^9$ neutrons/cm$^2$ $^{252}$Cf), or for 3 years (at $15 \times 10^{12}$ electrons/cm$^2$)
Hybrid APDs
(Active Pixel Devices)

• Massimo Caccia
  – readout pitch > pixel pitch
  – prototype tested
  – charge sharing efficiency demonstrated
  – next step ⇒ beam test of improved device

• Gianluca Alimonti
  – first “3-D” detectors fabricated
    • leakage currents 1/4-1 nA/mm³ (T_{room})
    • low depletion voltage
    • active edges
  – Rad-hard XTEST2
  – bump bond yields good
  – next year ⇒ prototype system
Hybrid detector with interleaved pixels between the output nodes

\[ \text{readout pitch} = n \times \text{pixel pitch} \]

- Large enough to house the VLSI front-end cell
- Small enough for an effective sampling
Due to the capacitive charge division, a particle will induce a signal on the surrounding pixels beyond the diffusive charge carrier spread.
Charge sharing II

- Laser spot
- NO diffusion, capacitive coupling only
- Diffusion and capacitive coupling with a 25 µm pitch
  Resolution < 25 µm/√12

Read out pixels
Interleaved pixels
Detector Development

Good timing!

Reduction of distance between electrodes:
- Reduction of drift time
- Reduction of depletion voltage

Charge collection time from a 3D cell, 50µ pitch, track parallel to the electrodes midway from central p and corner n.
XTEST2 Initial Prototype

To test feasibility, a prototype (XTEST2) was fabricated in HP 0.5 μm; going to .25 μm technology it is expected to fit in 50X50 μm (or 40X60 μm)
Interconnect Concerns

- Excellent SNR and Timing, but…

Assumption all charge is collected is FALSE!

For faster trigger time, even 100fF stray C would yield to SNR about 20.

For larger stray C the degradation may become unacceptable.

Test bumps for real measurement (evaluation from first principles is quite complex)
Bump bonding Results

- No open bump-to-bump connection observed out of 21120
- About 20% of chips bad (learning chips…)
- Using final “recipe”, the remaining 80% had a rate of inter row shorts of about one in a thousand
Monolithic APDs
(CMOS)

- G. Deptuch
  - prototype tested with beam
    - 64 x 64 pixel arrays
  - next year ⇒ increase size
    - ~ 10 cm
  - outstanding potential
    - rad-hard
    - high precision
    - ultra thin
    - low cost
  - issues to address
    - expand to system
    - power
Performance studies

• Bruce Schumm
  – aggressive scenarios (just to see)
    • improved resolution ($\Rightarrow 1 \mu m$)
    • smaller beampipe ($\Rightarrow 0.5 \text{ cm}$)
    • greater radial extent ($\Rightarrow 11 \text{ cm}$)
    • thinner layers (and pipe) ($\Rightarrow 0.06\% X_0$)
  – conclusions:
    • good central tracking vital
    • spatial resolution and beampipe radius lead to substantial improvements

• Akiya Miyamoto
  – flavor tagging
  – conclusion:
    • significant improvement with inner radius of 1.2 cm vs. 2.4 cm
Performance studies
(continued)

• Toshi Abe
  – heavy jet tagging
  – ZVTOP installed into LCD simulation

• Stefania Xella
  – flavor tagging with neural net including ZVTOP
  – update for new TESLA geometry
  – future ⇒ ZVTOP3, vertex charge, dipole charge

• Jim Brau
  – detector parameters and Higgs BRs
Performance studies
(continued)

- Marco Battaglia
  - 3 Tev - CLIC
  - extreme energies lead to some very long decay lengths (several cm)
  - proposes counting tracks with pulse height information
  - demonstrates viability with simulation of $\sigma (e^+ e^- \rightarrow b \overline{b})$ determination
Summary of LCWS2000

- Progress continues to advance on many fronts
  - CCDs
    - R&D to advance the already demonstrated exceptional system-level performance
  - Hybrid APDs
    - prototypes with charge sharing understood
    - “3-D” detectors fabricated
  - Monolithic APDs
    - effort to capitalize on industry standards
    - first chip shows extraordinary promise
  - Performance simulations
    - tradeoffs becoming clearer
Future Directions

• Continue progress on all fronts
  • CCDs
  • Hybrid APDs
  • Monolithic APDs

• Performance simulations
  • Refine our understanding of the impact of detector trade-offs on physics performance

• We will be able to exploit the exceptional physics opportunities of the LC