Fine grained SiW ECAL for a linear collider detector
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- ECAL Design Requirements
- The “SD” Detector
- Silicon and Electronics
- Warm versus Cold
- Timing resolution
- Plans

Si-W work – personnel and responsibilities

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Primary ECAL Design Requirements

- Optimal contribution to the reconstruction of multijet events:
  - Excellent separation of $\gamma$’s from charged particles
    \[ \textit{Efficiency} > 95\% \text{ for energy flow} \]
  - Good reconstruction of $\pi^\pm$, detection of neutral hadrons
  - Good linkage of ECAL with HCAL
  - Reasonable EM energy resolution ($< 15%/\sqrt{E}$)

Physics case: jet reconstruction important for many physics processes.
A principal goal of a linear collider is the determination of Higgs branching ratios using the processes:

\[ e^+ e^- \rightarrow Zh \]
\[ e^+ e^- \rightarrow h\nu\bar{\nu} \]

Excellent jet energy resolution is needed for the later process. Precision tests may also be of interest, e.g., measurement of quartic gauge couplings:

\[ e^+ e^- \rightarrow ZZ\nu\bar{\nu} \]
\[ e^+ e^- \rightarrow WW\nu\bar{\nu} \]

Use all final states.
• Reconstruct Bhabhas and deconvolve luminosity spectrum

  – Position resolution $\sim 100\mu m$, bias $\sim 25\mu m$ in endcap

  – Good energy resolution for 500 GeV electron showers.

Luminosity spectrum is important for

• $t\bar{t}$ threshold ($m_t$, $\alpha_s$, $t\bar{t}h$ coupling)

• $e^+e^- \rightarrow f\bar{f}$, important for limits on extra dimensions and "contact interactions"
• Position resolution important for understanding single hard photons from beamstrahlung

\[ \sqrt{s'} = \sqrt{1 - \frac{2 \sin(\theta_f + \theta_{\bar{f}})}{\sin(\theta_f + \theta_{\bar{f}}) - \sin \theta_f - \sin \theta_{\bar{f}}}} \]
Well understood energy resolution needed to understand linac beam energy spread

(NLC 500 Results from Torrence and Woods – beamstrahlung off)
• Reconstruct \( \tau \)'s and measure polarization (separate \( \pi \), \( \rho \), \( a_1 \), e's)

\( \tau \)'s are important in many ”New Physics” models:

– In many SUSY models staus are the lightest sfermions

– Many models have special couplings for the heaviest generation (extra couplings may explain large top mass)

– Tau polarization may be important in differentiating New Physics scenarios from each other
Secondary ECAL Design Requirements

- Excellent electron identification in jets (tag and b/c quarks)
- Partial reconstruction of b/c hadrons in jets
- Good $\gamma$ impact resolution for long lived SUSY neutrals
  $\sim 1 \text{ cm}$
- Good background immunity
  - Bunchlet identification
  - High granularity
SD ("Silicon detector")

Design constraints impacting calorimetry
(See talk by M. Breidenbach at Cornell*)

- Excellent jet-energy reconstruction using combined tracking and calorimetry (i.e. “energy flow”)

- Excellent momentum resolution for lepton pairs in processes such as (e.g. \( e^+e^- \rightarrow hZ \rightarrow \mu^+\mu^-X \))

- Excellent reconstruction of detached vertices from B’s (e.g. 5 layer CCD vertex detector)

- Cost compatible with \( \sim 5\% \)/detector of machine cost, perhaps $350M/detector

*http://blueox.uoregon.edu/~lc/cornell-detectors.html
• Main trade off is magnetic field versus detector radius with figure of merit

\[ f_p = BR^2 \]

• SD option: 5 T magnetic field, 1.25m calorimeter radius
  Optimization limited by maximum field
  Helps confine background \( e^+e^- \) pairs to beam pipe

• Stored Energy is less than TESLA ( \( \sim 1.5 \text{GJ} \) versus \( \sim 2.4 \text{GJ} \) )

• Reduces Si area and cost

• Places premium on ECAL granularity
  \( \text{(strive for a very dense detector)} \)
• 5 layer CCD vertex Detector
• Silicon tracker
• SiW ECAL (blue)
• HCAL inside of coil (brown)
• Coil (red)
Si-W Calorimeter Concept

Transverse Segmentation ~5mm
30 Longitudinal Samples
Energy Resolution ~15%/E^{1/2}
Electronics and Silicon Design
( Discussed in detail in Silicon Calorimetry Session )

- Use hexagonal 5mm pixels on 6 in wafers
- Use DC coupling to simplify wafer processing
- Readout chip bump bonded to wafer
- Electronics have a large dynamic range (0.1 - 2000 MIPs) with at least 0.5% resolution
- Cost first order insensitive to pixel size
- Power is main constraint on density
Importance of Granularity

- Figure of merit for energy reconstruction is

$$f_E = \frac{R_M}{R_{cal}}$$

where $R_M$ is the Molière radius and $R_{cal}$ is the inner radius of the calorimeter.

- The costs of the calorimeters, coil, and muon system have

$$\text{cost} \propto R_{cal}^n$$

where $n$ is $\sim 2 - 3$.

- Thus a 10% increase in the Molière radius of the calorimeter leads to a $> 20\%$ increase in cost of the detector for constant $f_e$.

- Conclusion: try and make the calorimeter as dense as possible.
Layout goal:

- **Brazed Joints**
- **Rolled Tungsten**
- **Circuit Board**
- **Silicon**

- **Layer Assembly**: 3.6 Meters, 1.1-1.3 Meters, Silicon, Circuit Board, Rolled Tungsten, Brazed Joints, >3.5mm
Critical parameter: gap between tungsten layers.

<table>
<thead>
<tr>
<th>Config.</th>
<th>Radiation length</th>
<th>Molière Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% W</td>
<td>3.5mm</td>
<td>9mm</td>
</tr>
<tr>
<td>92.5% W</td>
<td>3.9mm</td>
<td>10mm</td>
</tr>
<tr>
<td>+1mm gap</td>
<td>5.5mm</td>
<td>14mm</td>
</tr>
<tr>
<td>+1mmCu</td>
<td>6.4mm</td>
<td>17mm</td>
</tr>
</tbody>
</table>

Calice 3mm gap with 1.7m TESLA radius gives \( \frac{R_M}{R_{Cal}} = 13\text{mrad} \)
Important system level design issue for the calorimeter will be dealing with the heat produced by the electronics.

⇒ Largest unknown is power consumption of the electronics

![Graph showing temperature increase with length for different materials and power consumptions.]

Pessimistically assume cooling from one end only

![Diagram of calorimeter with labels for Inner Tracker, ECAL, and Cooling.]

2.5 mm of W 100mW
1.0 mm of Cu 100mW
1.0 mm of Cu + 2.5 mm of W at 100mW
2.5 mm of W 40mW

Length (cm)
Δ temperature deg. C
Warm – Cold Machine Differences

• ECAL design was developed in the context of a warm (X-band) linear accelerator. Will it still work for a cold (superconducting) machine?

• Main difference is the bunch structure:

<table>
<thead>
<tr>
<th>Technology</th>
<th>Repetition rate</th>
<th>Bunch train length</th>
<th>Bunch separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm</td>
<td>120 Hz</td>
<td>192 (0.270 µs)</td>
<td>1.4 ns</td>
</tr>
<tr>
<td>Cold</td>
<td>5 Hz</td>
<td>2820 (950 µs)</td>
<td>337 ns</td>
</tr>
</tbody>
</table>
Power Pulsing

- Assuming a $10\mu s$ turn on time for power pulsing, duty cycle of pulsed power:

  - warm $1/833$
  - cold $1/206$

- Non-pulsed is $\sim 1\%$ of “ON” power and dominates!

- Slower electronics possible for warm machine, so less power needed in "ON” state than for cold machine

Overall slight advantage for warm machine
Not a basis for choosing one or the other machines
Technology choice impact on electronics

- Current electronics provides timing at the few ns level for the warm machine (see next slide).

- Bunch ID for the cold machine is easy, but pipelined electronics needed (can't integrate over 2820 bunches).

- We expect that our electronics could be adapted for the cold machine, but effort is currently concentrated on warm machine.
Toy Monte Carlo Studies of Timing Resolution for 30 Samples

Assumptions – wild guesses – (waiting for real electronics model):

- Each MIP has 30 samples at random distances from the read-out chip
- Threshold for timing measurement is 8,000 electrons.
- Input FET has $g_m = 1.5\,\text{mS}$ and the noise contribution from the rest of the amplifier is equal to input FET except for the "floor" noise.
- The charge measurement has a noise floor of either 0 or 4000 electrons
- Time constant for charge measurement is 200 ns.
- Time constant for the time measurement is 50 or 200 ns.
- The noise signals in the timing and charge circuits are uncorrelated
- Random 5% channel to channel variation in threshold
- Random 1% event-to-event variation in threshold
- Random 5% uncertainty in constants used for correction.
- Reject time measurements far from mean
Sample Timing Results
200 ns time constant, no noise floor

Time versus charge for mips

30 sample average time
Including a 4000 electron noise floor (not needed in new electronics design):

30 sample average 200ns time constant

30 sample average time 50ns time constant
With no noise floor (eg use switchable feedback capacitor) and 50ns time constant:

Needs to be demonstrated in a test beam!
Si-W Status and Plans

- Design of first silicon detectors complete
  ⇒ Prototypes in hand

- Electronics design well advanced
  ⇒ Expect to be ready for submission in mid ’04

- Mechanical conceptual design started
  ⇒ ~1mm gap between layers without a copper heat sink may be possible

- Hope to build 30 layer test module within next two years