ECAL Design Studies and Scintillator/W/Silicon Hybrid

(Quite a lot of this talk overlaps with my (poor audio) talk from Dec 8th – but there’s a fair amount of new material – and for several of you most of the material is new).

Graham W. Wilson
Univ. of Kansas
Jan 8th 2004
Optimize what?

- Started looking mainly at **EM energy resolution** optimization in the context of $BR^2/R_M$ maximization.
- Have been looking in some detail at photon **position resolution** performance for various designs and pixel granularity
  - This wasn’t as trivial as I had anticipated.
- So far, the studies reveal more questions to answer than answered questions.
  - Potential large changes in performance from new approaches. Comparing particular “baseline” designs may be premature.

*I know that we are more interested in 2-particle separation than position resolution – but they are related.*
Recent ideas (some may be impractical)

Many inspired by discussions before/during Montpellier

- Rectangular Si pads (e.g., 2 mm X 10 mm) at start of shower
- W is expensive. Use W at front, Pb from ≈10 X0 on. (Pb int. length longer per X0).
- If correlations are useful, maybe even hybrid absorber plates ??
- Progressive sampling

- Thicken up Silicon cf present 300 µm design (DS mentioned this last time)
- Staggering of layers of Si in ECAL to remove position bias
- Make hybrid readout units independent (improves $d_{\text{conv}}$ resolution & PATREC ?)
- Temporal calorimetry. ($\Delta T$ between photon and 1.5 GeV $p_T$ π± is 0.6 ns for B=4T, R=1.7m) (Numbers corrected after previous presentation.)
Temporal calorimetry?

- For the same luminosity \((L = 2 \times 10^{34})\), the luminosity per bunch crossing is 1.6 times higher in warm cf cold. To some extent, event overlap scales directly with bunch crossing luminosity times no. of unresolvable bunches.

- For warm with \(\Delta T_{BX} = 1.4\) ns, something like 300 ps time resolution required for bunch ID. With \(\sigma_T = 2\) ns => say 15 bunches are consistent.
  - With bunch ID, event pileup: \(\text{warm} = 0.6 \times \text{cold}\)
  - With 2 ns timing, \(\sigma_T = 2\) ns: \(\text{warm} = 10 \times \text{cold}\)
  - Integrate over bunch: \(\text{warm} = 120 \times \text{cold}\)

=> Precision timing is obviously an advantage if the LC technology is warm
Temporal calorimetry for energy flow?

Idea: Use time difference between $\beta=1$ straight line (photon) and $\beta<1$ curved track (charged $\pi$, K, p)

- $\Delta T$ for 1.5 GeV pT tracks at $\cos \theta=0$, for $B=4.0$ T, $R=1.7$ m
  - $\pi$: 0.59 ns
  - K: 0.89 ns
  - p: 1.68 ns

- $\Delta T$ for 3.0 GeV pT tracks at $\cos \theta=0$, for $B=4.0$ T, $R=1.7$ m
  - $\pi$: 0.12 ns
  - K: 0.19 ns
  - p: 0.39 ns

Loopers have pT = 1.02 GeV here.

Conclusion: of order 100 ps resolution needed for time differences of the primary particle to be useful => looks impractical
Energy resolution for sampling W calorimeters

Si-W design (SLAC/Oregon) => cost and minimal $R_M$ require compromise on E resolution by minimizing Si area (30 layers) and (Si thickness (300 $\mu$m))

Scint-W design (Colorado) => inexpensive, more samples – but poorer granularity and larger $R_M$

Si-W-Scint. Hybrid (Kansas, K-State) => thin Scint. layers, cheaper, more samples (incl. Si), retain granularity, keep $R_M$ small
Need to minimise gaps, reduce space needed for fiber routing, by sharing fiber routing gaps among layers.

Assume 25% of scintillator thickness used for readout.
Energy resolution for sampling W calorimeters

42 layers = 2.5 mm W
56 layers = 1.75 mm W
75 layers = 1.4 mm W
135 layers = 0.78 mm W

Cost issues:
W cost \approx\text{ independent of thickness if rolled}

Si and scintillator scale as area, and can be more expensive if thinner.

Also plotted, CALICE, Asian, LCCAL, PbWO₄

SLAC Jan 8th 04
Graham W. Wilson
MIP response

GEANT4.5.0.p01
Range cut = 0.1µm

(started looking at pion response as well – but suspect hadronic interactions not enabled …)

There is a rumor from J-C B that later versions don’t have Landau mip response?
Energy spectra in Silicon per layer

David Strom was wondering whether the reason our G4 simulations with 0.1 µm range cut were giving better energy resolution was related to soft energy deposits.
Energy spectra in Silicon per pixel

These are the plots with energies per pixel:

SLAC Jan 8th 04
In December, I had shown that total energy deposits per layer < 1 MIP are not relevant to E-resolution discussion (the lower curve).

Now with **individual pixels**, the conclusion is that thresholds down to 0.3 MIP needed
Soft particles / 
E resolution ? 
Smaller pixels

Note: different samples used, so resolutions differ within statistics
Dynamic range

1000 1 GeV $\gamma$ events

1000 10 GeV $\gamma$ events

36 100 GeV $\gamma$ events

Getting geared up to look at dynamic range and noise issues vs pixel size for Si – should also do same thing for Scintillator.

SLAC Jan 8th 04
Particle Flow Studies – Photon Finder

Status

- photon reconstruction based on Steve Kuhlmann’s and Steve Magill’s algorithm
- ‘adapted’ to JAS3
- re-producing results
- machinery ready for further studies

Carsten Hensel
Plan to work on improving photon measurement, E-flow performance of various ECAL designs (not just SDjan03)
Hybrid Si-W-Scint. Calorimeter

- **Kansas-State**: T. Bolton, E. von Toerne, … getting started

Concept: Develop a cost-optimized ECAL with most of the advantages of the Si-W concept, but finer sampling, excellent time resolution and cost which permits placement at larger R.

Acknowledge: Si-W R&D work, tile-HCAL R&D.

Open to collaboration with interested parties: beam-tests needed to verify some of the novel features
Scint. Thickness – critical parameter for small $R_M$

Developments in tile-HCAL R&D, suggest light yields of 5 pe/mip/mm achievable with Silicon PMs – up to 20 pe/mip/mm with high QE devices.

Light-yield does not look to be overly critical. Can probably live with straight fibers.

Curves are for 2.5, 5, 10, 20, $\infty$ pe/mip/mm
Design studies using GEANT4

with Eric Benavidez (sophomore)

- All calorimeter designs have 30 $X_0$ of W (105 mm) to ensure adequate longitudinal containment and a fair comparison.

- GEANT4 studies are done primarily with 1 GeV photons (which are definitely longitudinally contained) so far.
  - “EM Showers are understood, therefore GEANT4 is correct” thought process, needs data reality checks
Software organization

• Documented at http://heplx3.phsx.ku.edu/~eric
  – Three major chronological functionality improvements

• Level 0 : examples/….TestEm3 “out of the box”
  – Basic checks of overall energy resolution for simple geometries

• Level 1 : hybrid ECAL with two different active media.
  – GEANT4 output saved as AIDA compliant tuple
  – Can be analyzed with JAS, PAW etc.
  – Allows studies of combined energy performance and longitudinal segmentation studies.

• Level 2 : pixelized ECAL
  – Add arbitrary transverse segmentation in each absorber
  – Allows studies of position resolution, clustering etc …

N.Graf in contact with us re using this for similar Si-W specific studies.
Three strawman hybrid designs

A super-layer (SL)

Studied with GEANT4
(range cut = 0.1 \(\mu\)m)

Sc-W-Sc-W-Si-W-Sc-W-Sc-W

HY75 (15 SL)              HY135  (15 SL)                HY42 (14 SL)

In each case the Si layer is chosen as 400 \(\mu\)m
Si + 2.0 mm G10 as in SDMar01 detector

So far: study uniform sampling structures.

SLAC Jan 8th 04
Graham W. Wilson
<table>
<thead>
<tr>
<th>HY75</th>
<th>HY135</th>
<th>HY42</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4mm W plates</td>
<td>0.778mm W plates</td>
<td>2.5 mm W plates</td>
</tr>
<tr>
<td>15 layers Si</td>
<td>15 layers Si</td>
<td>14 layers Si</td>
</tr>
<tr>
<td>60 layers of 1.5mm Scint.</td>
<td>120 layers of 1mm Sc</td>
<td>28 layers of 2 mm Sc</td>
</tr>
<tr>
<td>4 layers ganged</td>
<td>8 layers ganged</td>
<td>2 layers ganged</td>
</tr>
<tr>
<td>(30 pe/mip)</td>
<td>(40 pe/mip)</td>
<td>(20 pe/mip)</td>
</tr>
<tr>
<td>(if 5pe/mip/mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 super-layers</td>
<td>15 super-layers</td>
<td>14 super-layers</td>
</tr>
<tr>
<td>each with mip-detection</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| E res:                   | 10.4%/√E                | 7.7%/√E                  |
|                         | 14.3%/√E                |                           |
| Moliere radius:         | 19.3 mm                 | 21.4 mm                  |
|                         | 16.5 mm                 |                           |

(SDMar01 30X₀ W: 15.4%/√E, 15.5 mm)

SLAC Jan 8th 04
Graham W. Wilson
Correlation coefficient = -0.20 ± 0.01

Correlation improves resolution slightly – compensates for PE stats
• HY75 : -0.16 ± 0.01
• HY135 : -0.20 ± 0.01
• HY42 : -0.15 ± 0.01
• Not understood exactly how the negative correlation arises.
  – Adjacent active materials have high positive correlation.
  – Initial +ve correlation gradually becomes –ve as all the energy in the shower is integrated longitudinally and unitarity sets in ?

Leads to small improvement in energy resolution over naïve expectations !
Correlation Plots

Energy deposited in Sc and Si within each super-layer +vely correlated

Total energy starts out with +ve correlation between Sc and Si but eventually becomes negative
Energy in scintillator

Silicon note tails

Tungsten

G10

SLAC Jan 8th
Hybrid calorimetry?

- It could be that a novel choice of active detection media may allow an even stronger negative correlation.
- Plan to study dependence on layer thicknesses, and play with ideas like lead-loaded scintillator.
- It could be that some layers of neutron sensitive material could help the energy flow?
Tile-fiber response simulation

- At Cornell – showed first studies of optical simulation.
- Haven’t really followed up too much on this yet.
- Obtained DETECT2000 program (C. Moisan et al.) for optics simulation (C++ version of DETECT – G. Knoll et al) for modelling optical properties of scintillators and reflective materials using “unified optical model”– and designing assemblies – lot more light-weight than GEANT4 – and tuned to real applications. So maybe DETECT is the better way to do the optical simulation.
Cosmic ray test setup

Nov 9th, 2003

VME DAQ from scratch
Using LabView
8 2” PMTs with help from K-State.

1st QDC & TDC measurements this Tuesday.

Planning flexible testing capabilities of various scintillator/fiber geometries for light-yield, uniformity, time resolution.

V812 CFD
V775 TDC (35ps LSB 12-bit)
V792N QDC (100fC LSB 12-bit)
QDC spectrum

Pedestal is 160, rms<1channel

Fresh off the press

SLAC Jan 8th 04
Graham W. Wilson
Same signal as start and stop. RMS=50 ps. GOOD!

Not yet ready for prime time.
Jim Robbins working with us. EE with AutoCad experience

Stackable dark boxes for scintillator tiles in cosmic ray test setup => machine shop

Diagram shows Photonis XP2020 PMTs.
Transverse granularity for Si, Scint. tiles?

Shower profiles from OPAL Si-W.
Plots suggest that scintillating tiles of reasonable dimensions by themselves will not do the job.
Scintillator-based sampling cost may be dominated by photodetector channel count.

RM = 15 mm
• Standard lore: cell-size, d, should be of order the Moliere radius, $R_M$
  – If $d \gg R_M$, very little energy sharing with adjacent cells => poor position resolution
  – If $d \ll R_M$, many channels, diminishing returns
• Have studied square pixel sizes of 50, 16, 5, 1 mm
Regime of $d >> R_M$ is hard to deal with using standard ybar algorithm.

1 GeV photon

\begin{table}[h]
\begin{tabular}{|c|c|c|}
\hline
$\chi^2/\text{ndf}$ & 118.3 & 47 \\
\hline
P1 & 0.4552 $\pm$ 0.1518E-01 & \\
\hline
P2 & 0.6364 $\pm$ 0.6183E-01 & \\
\hline
P3 & 6.309 $\pm$ 0.1445 & \\
\hline
\end{tabular}
\end{table}
HY42 design ($R_M=16$ mm)

Coordinate measurement bias

Pixel size

$y_{\text{rec}} - y_{\text{true}}$ (mm)

$y_{\text{true}}$ (mm)

1 GeV photons

1 mm

5 mm

16 mm

50 mm

SLA
1 GeV photons

HY42 : using both Silicon and Scintillator.

Silicon only about 50% worse.

$\sigma = 10 \text{ mm}$

$\sigma = 3 \text{ mm}$

$\sigma = 2 \text{ mm}$

i.e. $2 \text{ mm}/\sqrt{E}$
Position Resolution if we could have 1mm x 1mm pixels!

• Using Silicon energy weighted position estimates for 1 GeV photons
  • HY135 (\(R_M = 19.8\) mm) \(\sigma_{pos} = 2.7\) mm
  • HY75 (\(R_M = 18.0\) mm) \(\sigma_{pos} = 2.5\) mm
  • HY42 (\(R_M = 15.6\) mm) \(\sigma_{pos} = 2.2\) mm
  • SI42a (\(R_M = 16.9\) mm) \(\sigma_{pos} = 2.0\) mm
  • SI42b (\(R_M = 13.5\) mm) \(\sigma_{pos} = 1.5\) mm
Superb Position Resolution for 1 GeV Photons

For illustration purposes only!:
Si-W, 42 layers, 1mm x 1mm pixels, $R_M = 13.5$ mm

1 GeV photons

Transverse segmentations much finer than 5 mm may be useful – Si strips?

Position residual (mm)
Position resolution from simple fit

Neglect layer 0 (albedo)

Using the first 12 layers with hits with $E > 180$ keV, combine the measured C of G from each layer using a least-squares fit (errors varying from 0.32 mm to 4.4 mm). Iteratively drop up to 5 layers in the “track fit”.

Position resolution does indeed improve by a factor of 5 in a realistic 100% efficient algorithm!

Still just $d/\sqrt{12}$!
Starting to grapple with some ECAL optimization degrees of freedom which are not yet fully appreciated.

The hybrid concept looks encouraging
  - There don’t seem to be unforeseen drawbacks of two active media
    - if anything advantages (-ve correlations)
  - The necessary thin scintillator layers appear feasible
    - Will soon be able to test this
  - By playing the strengths/weaknesses of Si vs Scint. (transverse granularity/cost/timing) against each other, we may design a better ECAL
Backup Slides

• (some of these are from Montpellier and not necessarily that relevant today)
5mm pixels, 10 GeV photon
Is superb photon position resolution useful?

- High energy $\pi^0$’s for sure.
- Many jet channels have applicable kinematic constraints – angular resolution may be just as important as energy resolution
  - But neutral hadrons may dominate uncertainties
How to move towards deciding among technologies/approaches?

- Need realistic cost models of various designs
  - The Pb or W decision seems almost entirely a matter of cost.
- What metric to use for performance comparison?
- Also tied in with global detector design particularly, B-field, tracking quality, $R_{ECAL}$.
ECAL Challenges

• Compact calorimeters with signals!
• Transverse segmentation to a fraction of the Moliere radius
• Cost-effective yet high performance design
• Sound mechanical design
• Establishing accepted ways to evaluate high-level particle-flow like performance of different designs

Major challenges for each approach

Si-W : thin active gaps, cost for acceptable R and E-resolution

Sc-W : thin active gaps, granularity

Crystals : long. segmentation

hybrid : thin active gaps, cohabitation
Estimating impact position of photons in a Cadillac ECAL

- Don’t need to use longitudinally integrated cell energies.
- Can try and identify the photon conversion and measure its position from nearby (in depth) energy deposits
- Specialized shower max detector or photon conversion point finder…
- Can offset pixels cancelling wiggles (to some extent). Colorado group have looked at this
- I learned from J-C Brient yesterday that the position resolution estimate in the TDR assumed successive layers are staggered by 1 mm.
Estimating impact position in projective calorimeters

• Several Methods
  – Standard one. Form estimator ybar by energy weighting the cell centers.
  – Alternative. Modify estimator by giving more weight to the tails (eg. weight = E^{0.45})
  – Shower fit. Adjust impact point to give best fit between measured cell energies and integrals of the average shower profile over each volume pixel
  – Use cell sharing function

• All subject to bias
  – should be correctable at some level
  – but maybe at the expense of “resolution”.
The fact that the wire chamber resolution ultimately limited the position resolution of this calorimeter (to $\sim 200 \, \mu$m at high energies) illustrates the very precise reconstruction of the four-vectors of electrons (and photons) that can be achieved with high-resolution calorimeters that measure the showers developed by such particles.

![Diagram](image.png)

**HY42**

**Fig. 7.13.** The position resolution for em showers in a variety of calorimeters as a function of the effective Molière radius of one calorimeter cell. The position resolution is given in mm ($a$) or in Molière radii ($b$).

In Figure 7.13, a compilation is made of the position resolution of a wide variety of...
Parametrizations

- EM Energy resolution:
  \[ \sigma_{E}/E = c_{1}/\sqrt{E}\text{(GeV)} \oplus c_{2} \]

- HCAL Energy resolution:
  \[ \sigma_{E}/E = c_{3}/\sqrt{E}\text{(GeV)} \oplus c_{4} \]

- Tracker resolution:
  \[ \sigma_{p_{T}}/p_{T}^2 = c_{5} \text{ (GeV}^{-1}) \]

Central values:
- 10%/$\sqrt{E} \oplus 1%$
- 50%/$\sqrt{E} \oplus 4%$

Keep 4 parameters fixed at central values, vary 5th.
Motivation for good ECAL stochastic resolution
What LC ECAL performance characteristics?

EM energy resolution, calibratability, longitudinal segmentation, affordable, angular resolution, pointing resolution, electron ID, timing resolution, response to charged hadrons, response to neutral hadrons, noise, cross-talk, compensating, background immunity, bunch ID, dynamic range, radius, upstream material, alignable, particle/particle resolving power – particularly photon/charged hadron resolving power, transverse segmentation, Moliere radius, radiation length, interaction length, longitudinal containment, albedo, dE/dx, quantum fluctuations, hermeticity, uniformity, neutral hadron ID, B-field, jet energy resolution, jet angular resolution, MIP reconstruction

Particle flow paradigm suggests B $R^2/R_M$ as one of the relevant figures of merit
• Calorimeter design optimization.
  – Studying with full shower simulation.
  – Using optics simulation in tile-fiber design and testing studies.

• Demonstrating basic performance characteristics
  – Light yield for thin scintillating tiles
  – Response uniformity
  – Scintillator/WLS/Photo-detector for timing
  – Fiber routing for compact calorimeter
  – Sound mechanical design
  – Good quality thin absorber plates (sintering is cheap ..)
  – Photo-detector characteristics