Investigation of ECAL Concepts Designed for Particle Flow

Classification (subsystem)

Detector: electromagnetic calorimeter (barrel, endcap, low-angle)

Personnel and Institution(s) requesting funding

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Collaborators

We have listed the names of various people with whom we have been in discussion with regarding participation in this and related projects.

Project Leader

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Project Overview

The project goal is to investigate electromagnetic calorimeter (ECAL) design concepts suited to the linear collider physics program. The principal physics design criteria for the ECAL are i) hermeticity ii) the precise measurement of jet energies using particle flow and iii) a design suited to a general purpose experiment. All these criteria are closely tied to the overall detector design concept, and therefore this project is being coordinated with the detector design studies. In the following sections we outline some of the reasons for highlighting these criteria and discuss their impact on the ECAL concept.

[Hermeticity] For e^+e^- center-of-mass energies beyond m_Z, physics processes with W's or Z's decaying in channels with 1 or 2 neutrinos occur frequently. Potential new physics such as supersymmetry leads to final states with characteristic missing transverse momentum. A principal detector goal is that events with significant missing transverse momentum should not be faked by Standard Model processes without neutrinos. It is of paramount concern that high transverse momentum particles, particularly photons, are detected with zero inefficiency. In the very forward region, (nearer the beam than the forward tracking), extremely efficient detection of electrons from two-photon processes is mandatory. It can also be necessary to detect muons and mips in such regions depending on the event topology.

The hermeticity requirements influence the ECAL design as follows: (i) need to avoid pointing cracks (ii) requirement to detect minimum ionizing particles (iii) elimination of "intruders" such as cosmics and halo muons (iv) reasonably uniform performance over the complete solid angle

[Particle Flow] In the particle flow method of jet energy measurement [1], the ECAL is used to measure the energy, polar angle and azimuth of photons in hadronic jets. A major requirement is to avoid double-counting of charged particles and photons in the visible energy measurement. This is most easily achieved by placing the ECAL at large radius.

The essential issue for the ECAL is measuring the 3-momenta of the photons over a dynamic range of between about 100 MeV and 500 GeV.

We have studied the intrinsic contribution to jet energy resolution arising from electromagnetic energy resolution [2] and we confirm that fractional energy resolution of $\approx 10\%/\sqrt{E}$ is necessary in order to not appreciably degrade the potential jet energy resolution of $18\%/\sqrt{E}$. For a realistic particle flow algorithm in a detector where the overall jet energy resolution attains $30\%/\sqrt{E}$, we expect this resolution would be dominated by confusion issues, and one could consider relaxing the electromagnetic energy resolution requirement substantially (perhaps by a factor of two) if jet energy resolution was the only physics concern (it isn't !).

The measurement of τ-lepton decays places severe constraints on the separation of charged hadrons from photons from π^0 decay. Kinematic reconstruction of events containing τ-leptons places rather stringent demands on the ECAL. (HCAL is relatively unimportant since neutrons are absent and K_L^0 are rare).

Another aspect of the calorimeter design which should not be overlooked is the detection and measurement of hadronic jets in the forward region where the charged particle tracking is likely to be compromised, specialized functions need to be accommodated (eg. Bhabha acolinearity measurement, luminosity measurement), and in general the environment is less conducive to full reconstruction (pile-up from $\gamma\gamma$ events).

[Design suited to general purpose e^+e^- experiment] Detection and precision measurements of electrons and photons is an essential element of an e^+e^- experiment. The measurement of Bhabha's and the $e^+e^- \to \gamma\gamma$ process are part of the basic program and are expected to play an important role in the measurement of absolute luminosity and the differential luminosity spectrum. Photons from initial and final-state radiation are often crucial aspects to doing some of the physics. With the prevalence of "radiative-return" events and events from two-photon interactions, the tagging of the initial-state photon or a scattered electron can be essential to physics analyses. $\ell\ell\gamma$ events will be a useful cross-check of the center-of-mass energy determination.

Given that we don't know what new physics will be explored at the linear collider, there is little strong guidance on the required energy resolution for the ECAL. One scenario which deserves more investigation, as it is one of the more compelling constraints on the ECAL resolution, is the measurement of the Higgs branching ratio to $\gamma\gamma$ presuming a Higgs mass of around 120 GeV. This was studied in [3]. The best measurement will come from the WW fusion channel ($e^+e^- \to \nu_e\overline{\nu_e}\gamma\gamma$) at the highest center-of-mass energy which has to compete against a large non-Higgs Standard Model background. This measurement would be complementary to LHC because together with other channels the BR could be measured directly. For similar reasons to LHC, the ECAL mass resolution directly influences the measurement precision. For this kind of application, the constant term in the energy resolution can be just as important as the stochastic term, and so an ECAL design which minimizes non-uniformities and can be easily calibrated is important.

Detector Design Considerations relevant to ECAL

The final detector designs will be heavily influenced by the choices made for the calorimetry. Some of the main design parameters which need to be considered are: the chosen B-field, the inner radius of the ECAL, the radius of the coil, and the aspect ratio (ie. the polar angle at which to change from a barrel to an endcap geometry).

Much of the current ECAL effort has been directed to applying the principles used very successfully in the limited solid angle LEP/SLC Silicon-Tungsten ECALs used for luminosity measurements to a full solid angle detector [4]. This approach is very attractive. Existing studies have characterized reasonably well the potential performance of the design studied for the TESLA TDR [5]. The main potential drawback is the cost, which may force the detector design to small radius, large field and fewer sampling layers, as in the SiD approach.

To date, there has been relatively little work focussed on ECAL concepts which are well matched to the goals of particle flow at large radius. Given that there are good reasons to believe that a larger detector has a better physics potential, [11], this should be seen as an area of critical need.

The University of Kansas group has been working on developing ECAL concepts which have the potential to be competitive with Si-W in properties where Si-W excels while substantially more cost effective and offering complementary capabilities in terms of energy resolution and timing resolution. A more cost effective solution would naturally lead to the possibility of building a much larger detector which would be the most effective way of ensuring particle separation for particle flow measurements. This would naturally fit well into the large and huge detector design studies.

We have been studying compact hybrid sampling ECAL structures with Tungsten absorber, with both silicon sampling gaps and scintillator sampling gaps. This approach promises the cost-effective use of silicon for shower pattern recognition and position measurement, while using cheaper scintillator layers as the main sampling medium. With this approach we have studied the simpler configurations of only Silicon sampling and only Scintillator sampling too. The current favored approach for the scintillator sampling is using scintillator-tiles with wavelength shifting (WLS) fiber readout to "on-tile" Silicon-Photomultiplier photo-detectors as employed in the CALICE MiniCAL [13]. The Silicon-PM has obvious advantages in terms of hermeticity, operation in B-field, and calibration (individual photo-electron peaks can be resolved). Features which need to be taken into account/mitigated are the noise and saturation characteristics.

We have been very encouraged by superb position resolution estimates for photons with Si-W sampling structures (300 μm for 1 GeV photons) assuming probably unrealistically small 1mm^2 pads [7] in a Si-W structure with a Moliere radius of 15 mm (see Figure 1). We are starting to envisage a new kind of particle-flow ECAL.

The essential issue about granularity is the separation of photons from charged tracks. This is best achieved by doing this separation at the longitudinal coordinate near which the photon converts. Our current ideas are to have a calorimeter which might consist of the following sections in depth :

- PAIRCAL: About 5 radiation lengths with Tungsten absorber and fine transverse granularity Silicon sampling layers (sampling at least every 0.5 radiation lengths). This device would pin-point the initial photon-conversion both in terms of transverse coordinate and longitudinal coordinate with very high efficiency. It may also be used to add some precise outer space points on high momentum tracks.
- SHOWERCAL: About 10 radiation lengths with Tungsten absorber and coarser transverse granularity Silicon sampling layers. The sampling would be at least every radiation length. More frequent sampling with some scintillator layers could be considered, but would need to be rather compact longitudinally. This device would do the bulk of the energy measuring while retaining excellent pattern recognition abilities before and after the EM shower maximum.

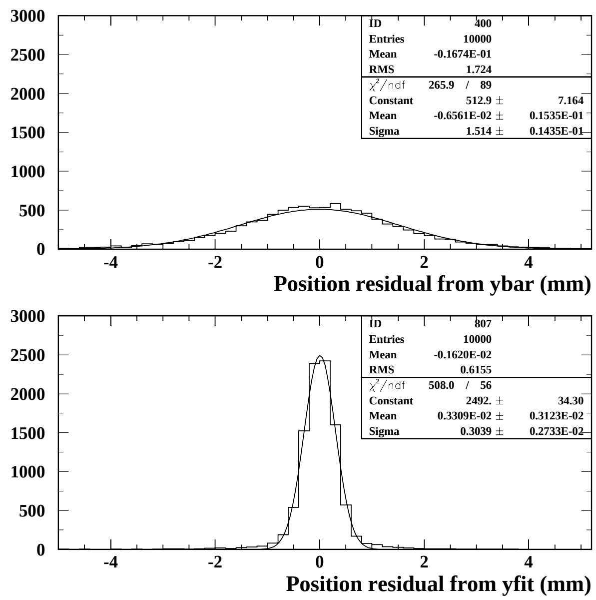

Figure 1: *Measured position resolution in one dimension for 1 GeV photons in a Si-W calorimeter with 42 sampling layers with 1mm^2 pads. Upper graph shows the results from the longitudinally integrated center-of-gravity of the shower with a resolution of 1.5 mm. The lower graph shows the results of a weighted "track-fit" to the first 12 layers. A position resolution of 300 μm is achieved with 100% efficiency.*

- EM-TAILCAL: About 15 radiation lengths of cheaper technology ECAL still with sampling frequency of at least every radiation length. The absorber could be Tungsten or Lead. Lead would have the advantage of a better radiation length to interaction length ratio, and being cheaper. Longitudinal compactness requirements would be less severe. This portion should also provide functionality at least as good as the chosen HCAL technology, but needs to be analog.

This kind of arrangement is probably better suited to detector integration than the hybrid designs we have been exploring. Each potentially different technology has its own radial space. However, the radial subdivision may also entail new difficulties with calibration and pattern recognition which would need to be investigated/minimized.

Broader Impact

The project will support participation of undergraduates in research.

Our on-going work with setting up cosmic-ray test facilities will be done in such a way that we can use the apparatus as part of an open-day type demonstration in conjunction with a diffusion cloud-chamber we recently acquired. This apparatus will allow the general public to see and hear cosmic-ray muons.

We are interested in making movies which depict what happens in an e^+e^- interaction as the reaction products propagate through the detector and interact. The idea will be to capture images of a simulated event at appropriate time intervals after the interaction. Particularly relevant to this project, is to depict well the electromagnetic shower development.

Results of Prior Research

[Progress to Date]

We have made progress on a number of issues related to this proposed project.

- We have studied the dependence of jet energy resolution on the intrinsic resolution of the tracker, the ECAL and the HCAL for all jet flavors. This study was carried out by Darius Gallagher (graduate student) under the supervision of Wilson. Results were reported at the Cornell, Summer 2003 meeting.
- Studies related to the importance of hermeticity in the detector design were described in the TESLA TDR by Wilson [6], and related results were reported in a plenary talk at the SLAC January 2004 ALCPG meeting [8]. Gallagher has been exploring the ability to detect smuons in low visible energy scenarios where hermetic forward coverage is essential and the beam-hole caused by a large crossing-angle may be a hard limitation.
- Undergraduate student, Eric Benavidez, has been instrumental in developing our GEANT4 capabilities under the supervision of Wilson. We have developed simulations related to the following:

  optical tracking of photons in scintillator tiles

  simple sampling calorimeter test-beam geometries with arbitrary sampling media

  pixelised sampling calorimeters
- We have used these simulation tools to study several issues relevant to the ECAL design concept. These have been reported at the regular meetings both nationally and internationally [9]. Some of the main results are the following:

Characterization of the energy resolution dependence on absorber and active material thicknesses. Studies have been done for Si-W, Scint-W and hybrids with W absorber and both Si and scintillator active layers. In particular we demonstrated that thicker Silicon layers which lead to a higher sampling fraction benefit the energy resolution. Examples are shown in Figure 2 and Figure 3.

We have investigated the position resolution for photons as a function of the cell size. We have found, (as we expected), that cell sizes much smaller than the Moliere radius, do indeed lead to much better position resolution. Even with 1mm pads, we still found a resolution of pad-size/$\sqrt{12}$.

Study of the correlation between the Silicon and scintillator response in hybrid structures. An anti-correlation of as much as 20% was observed which goes in the direction of improving the energy resolution compared to that which would be obtained with pure Si-W or pure Scint.-W. This observation offers the possibility that novel media may lead to larger (and more beneficial) anti-correlations.

Study of some of the dynamic range issues associated with measuring beam energy electrons and photons at the highest center-of-mass energies.

Observation that studies reported by other groups were using cutoffs in the electromagnetic simulation which were affecting quantitatively their conclusions.

- We have developed a VME data acquisition system with multi-channel QDC's and TDC's for measurements with scintillator-based detectors. Undergraduates Eric Benavidez and Jonathan van Eenwyk have worked together with Wilson on the commissioning of this system. We have been using this with a cosmic-ray trigger, as a set-up designed for testing scintillator-tile assemblies. We are currently getting this running with scintillator tiles from OPAL described in [12]. We also have some sources which will be used in this study.
- We have been in communication with a number of potential collaborators, whom we are interested in collaborating with on this or related projects.

  M. Ronan, (LBL) : large detector concept

  R. Frey, D. Strom (Oregon) : Si-W

  J.C. Brient, (Ecole Polytechnique) : Si-W ECAL

  M. Thomson, D.R. Ward, (Cambridge), calorimeter reconstruction

  K. Kawagoe (Kobe), T. Takeshita (Shinshu), scintillating-tile ECAL

  B. Dolgoshein (MePHI), M. Danilov (ITEP), Silicon-PM

  V. Korbel, F. Sefkow (DESY), tile-HCAL applied to ECAL

  V. Zutshi (NIU)

  S. Kuhlmann, S Magill (Argonne)

  P. Checchia (Padova)

  D. Onoprienko, E. von Toerne, T. Bolton (Kansas State)

  P. Baringer, A. Bean, D. Besson (Kansas)

  N. Graf, A. Johnson (SLAC)

[Results of Grant most closely related to our LC research]

The grant most closely related to our LC research was the $7500 (including overhead) contribution we received from the UCLC planning grant in FY2003. The award period was July

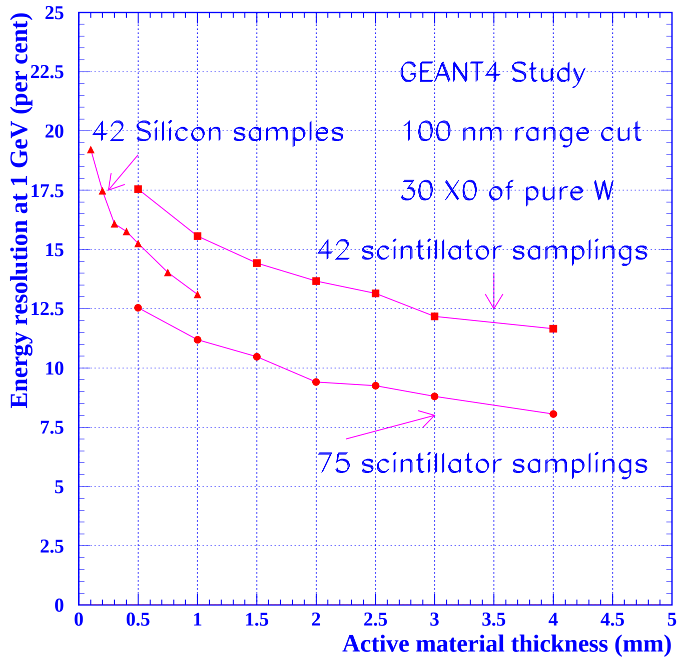

Figure 2: *Dependence of energy resolution for 1 GeV photons on sampling layer thickness for 3 different ECAL configurations. Each ECAL has 30 radiation lengths of Tungsten absorber (ie. 105 mm of W).*

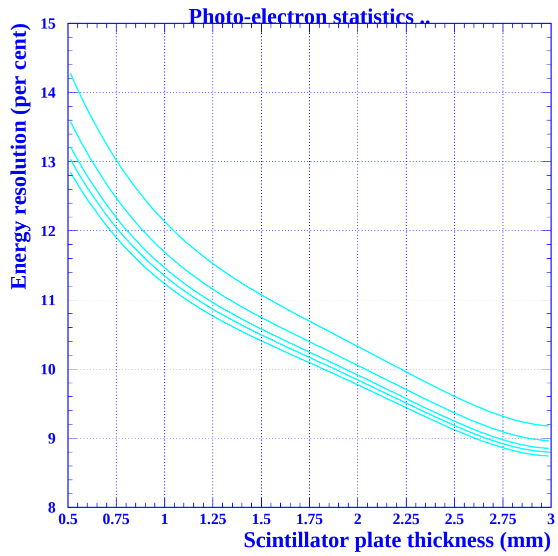

Figure 3: *Energy resolution for 1 GeV photons vs scintillator sampling thickness for 75 sampling layer W calorimeters with 30 radiation lengths of W. The lowest curve shows the contribution from only sampling fluctuations. The four upper curves include the effect of photo-electron statistics with assumptions of 2.5 photo-electrons/mip/mm (upper curve), 5.0 pe/mip/mm, 10.0 pe/mip/mm and 20.0 pe/mip/mm. Note the suppressed zero.*

2003 to September 2004. This was targeted at our proposal entitled "Investigation and Design Optimization of a Compact Sampling Electro-magnetic Calorimeter with High Spatial, Timing and Energy Resolution".

The funds were used to partially fund our undergraduate researchers, Benavidez and van Eenwyk. They were also used substantially for travel to workshops at which results were presented and opportunities to discuss with colleagues and future collaborators presented themselves.

Results related to this grant are described above, and in more detail on the following web page and related links [10].

This proposal is not for renewed support, but it does differ a little in scope compared to the previous proposal to UCLC, in that now that the accelerator technology choice has been made, and a short bunch crossing time has been excluded, we have de-emphasized timing resolution.

Facilities, Equipment and Other Resources

Machine shop with two experienced machinists. CAD technician. Electronics engineer and electronics technician. Instrumentation Design Lab. Linux cluster with 7 high-end dual-CPU machines. Clean rooms with facilities designed for Silicon detectors. Cosmic-ray test-stand with VME data acquisition. Variety of check sources particularly ones with internal conversion electrons.

FY2005 Project Activities and Deliverables

We will investigate the performance characteristics of various ECAL concepts.

We will work on the photon reconstruction package for the particle flow algorithm. Carsten Hensel (post-doc) will take the lead on this in collaboration with Norman Graf (SLAC). This activity should be beneficial to all ECAL concepts and detector design concepts. Deliverables will include characterization of the photon reconstruction performance. We are very keen to also investigate the quality of reconstruction of photons inside hadronic jets (ie. near interacting charged particles). A useful figure of merit, which factorizes out neutral hadron effects, may be the reconstructed visible energy in hadronic Z decays where there are no neutral hadronically interacting particles, nor neutrinos.

Depending on the realism achieved in the detector design simulation, we would also plan on characterizing the expected photon response over the full solid angle paying particular attention to the regions where hermeticity might be compromised.

We are very interested in getting involved in test-beam tests of particularly photon/charged-hadron separation, and anticipate getting involved in current Si-W projects.

Investigation of Silicon-photomultipliers.

FY2006 and FY 2007 Project Activities and Deliverables

This proposal is targeted at the development of an electromagnetic calorimeter design concept in calendar year 2005. We foresee future funding requests for the validation of design choices and construction and testing of a prototype once we have converged on an electromagnetic calorimeter design concept.

Budget justification: University of Kansas

The budget and scope we have outlined for this project is primarily for the design of a concept. In this respect a majority of the costs are associated with personnel (in the form of undergraduate research support), and the support for travel. The travel will be associated both with software development, particularly in collaboration with SLAC, and also work related to the detector design concept which will involve travel to discuss with collaborators both in Europe and Asia, and participation at the Snowmass workshop.

The materials and supplies items are associated with fabrication of scintillating-tile assemblies and associated photo-detectors.

Three-year budget, in then-year K$

Institution: University of Kansas

Item	FY2005	FY2006	FY2007	Total
Other Professionals	0	0	0	0
Graduate Students	0	0	0	0
Undergraduate Students	6	0	0	6
Total Salaries and Wages	6	0	0	6
Fringe Benefits	0	0	0	0
Total Salaries, Wages and Fringe Benefits	6	0	0	6
Equipment	0	0	0	0
Travel	10	0	0	10
Materials and Supplies	5	0	0	5
Other direct costs	0	0	0	0
Institution 2 subcontract	0	0	0	0
Total direct costs	21	0	0	21
Indirect costs(1)	9	0	0	9
Total direct and indirect costs	30	0	0	30

References

[1] H. Videau, "Particle Flow", plenary talk in proceedings of LCWS 04, Paris, April 2004.

[2] D. Gallagher and G.W. Wilson, "Influence of Intrinsic Detector Resolution on Jet Reconstruction for an Ideal Particle Flow Algorithm", Cornell ALCPG workshop, July 2003. Draft writeup available at `http://heplx3.phsx.ku.edu/~darius/eflow/eflow.pdf`

[3] E. Boos, J.-C. Brient, D.W. Reid, H.J. Schreiber, R. Shanidze, "Measuring the Higgs Branching Fraction into Two Photons at Future Linear e^+e^- Colliders", LC-PHSM-2000-053 available from `http://www-flc.desy.de/lcnotes/`

[4] J. Brau, A. Arodzero, and D. Strom, Snowmass 1996 proceedings, pp 437-441.

[5] F. Badaud et al., "Si-W calorimeter performances", LC-DET/2001-058.

[6] TESLA Technical Design Report, March 2001.

[7] G.W. Wilson, "ECAL R&D News from the Americas", talk at ECFA workshop, Montpellier, France, November 2003.

[8] G.W. Wilson, "Physics Requirements for Detectors in the Forward Region", plenary talk, SLAC ALCPG workshop, January 2004.

[9] `http://heplx3.phsx.ku.edu/~graham/ecaltalks.html`

[10] `http://heplx3.phsx.ku.edu/~graham/kulcd.html`

[11] G.W. Wilson, Plenary talk on "Detector Designs with Large Volume Gaseous Tracking", ALCPG meeting, Victoria, B.C., Canada, July 2004.

[12] G. Aguillion et al., NIM A417 (1998) 266.

[13] V. Andreev et al., "A High Granularity Scintillator Hadronic-Calorimeter with SiPM Readout for a Linear Collider Detector", DESY 04-143, October 2004.