

**A Calorimeter Based on Scintillator and Cherenkov
Radiator Plates Readout by SiPMs**

(New Proposal)

Calorimetry

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Institutions

University of Washington

Fermilab

Funds requested

FY06: \$90,503

FY07: \$93,008

A Calorimeter based on Scintillator and Cherenkov Radiator Plates Readout by SiPMs

Classification (subsystem)

Calorimeter

Personnel and Institution(s) requesting funding

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Project Overview

We propose to study the design of a calorimeter for the ILC experiment constructed by using plastic scintillator and Cherenkov radiator plates to achieve compensation based on the dual readout principle. We also will investigate the possibility of using the Cherenkov light observed in hadron jets to help separate the neutron components and the charged hadron components that is an essential requirement in the content of the particle flow algorithm (PFA) for jet energy reconstruction. Both the plastic scintillator plates and the Cherenkov radiator plates will be readout by using imbedded WLS fibers and SiPM [1] mounted directly on the plates. We believe with sufficient R&D effort, a design of a compact and fully compensated calorimeter with an EM energy resolution less than $10\%/\sqrt{E}$ and a jet energy resolution $(20-30\%)/\sqrt{E}$ plus a constant term of $\sim 1\%$ can be developed.

The concept of using Cherenkov radiation to achieve compensation in a homogeneous hadron calorimeter was first studied using computer simulation method by D.R. Winn and W.A. Worstell [2] and in 2003, a proposal titled "Cherenkov compensated calorimetry" lead by Yasar Onel of University of Iowa was submitted to the LCRD program [3] for further studying this method. Studied by another group lead by Richard Wigmans using quartz fiber and scintillating fibers imbedded in copper have shown very promising results [4] based on this dual readout concept. Although sharing some common design principles, the configuration of our proposed calorimeter are quite different from the one described in ref. [4].

The calorimeter configuration that we are proposing will have several advantages. Its main advantage is the possibility of achieving compensation by exploring the dual readout technique. The hadron cluster shape defined by the Cherenkov radiation will be narrow that may help the separation for charged and neutron hadron clusters in the PFA scheme. The fine segmentations both in the transverse and longitudinal direction will allow the identification of electromagnetic and hadron showers. This design also will be better adapted to the environment of a collider detector.

1. Introduction

Jet detection with good energy resolution is fundamentally important for physics and also is one of the most challenging tasks at the International Linear Collider with the central of mass energy at 1 TeV. The three main detector concepts at ILC are investigating different approaches in order to meet the very challenging requirements. The GLD concept has chosen a calorimeter baseline that uses plastic scintillator plates as active media and tungsten/lead plates as passive absorbers. Several different technologies are been investigated by LDC and SiD detector concepts. In the DHCAL design, the technologies used in EM section and the Hadron section are completely different. One of the EM calorimeter choices is highly segmented silicon pad detectors with thin tungsten absorber plates. The hadron section is based on binary readout with very small (1 cm^2) detector cells. The total readout channels for the EM and hadron calorimeters combined can exceed 100 million in this design. These calorimeter design concepts rely on the Particle Flow Algorithm (PFA) to achieve the required jet energy resolution. The calorimeter depths (EM plus hadron) for the 3 main detector concepts are about 1.5 meters and have 5 to 6 interaction lengths. The absorber materials being considered are tungsten, lead or steel.

We propose to study a different design of a calorimeter constructed by using plastic scintillator plates, Cherenkov radiator plates and structural material. In addition to the plastic scintillator plates used as active detectors in the GLD concept, we propose to study the possibility of partially or completely replacing the passive absorber plates by Cherenkov radiator plates. The preferred Cherenkov radiator material will be high density lead glass. Heavy metal sheets can be inserted if we need to make the calorimeter more compact. The calorimeter will have both transverse and longitudinal segmentations that can be similar to that used in the GLD concept. Both the scintillator and Cherenkov radiator plates are readout by the new silicon photomultipliers.

The basic principle of achieving compensation in our proposal is the same as the one studied earlier and discussed in ref. [2],[3],[4]. As shown in Fig. 1, the calorimeter design of ref. [4] is based on the spaghetti calorimeter geometry with two types of fibers, the scintillating fibers and quartz fibers imbedded in copper absorber. The scintillating fibers are sensitive to both hadronic and EM components of the hadron showers and the quartz fibers are mostly sensitive to EM components. The large bundles of two different types fibers are separated at the outside end of the calorimeter and are routed to large photomultipliers. The compensation can be achieved on an event-by-event based on the two independent energy measurements by properly adjusting the relative energy scale between the EM and the hadronic components of the jets. In such a design, fibers are laid in the radial direction and run the full depth of the calorimeter without longitudinal segmentation. The energy response has an angular dependence and discriminating EM and hadron showers can be difficult especially for high energy jets in which many particles are densely packed together without knowing the depth of shower development from the longitudinal segmentations.



Fig. 1. The basic configuration of the DREAM calorimeter discussed in ref. [4].

2. Proposed detector configuration

Our proposed detector configuration is quite different from the DREAM calorimeter described above. The basic configuration of the calorimeter is shown in Fig. 2. Optimum segmentations and choices for active detector and passive absorber materials will be the subjects for the R&D program. Here, we provide some general discussions.

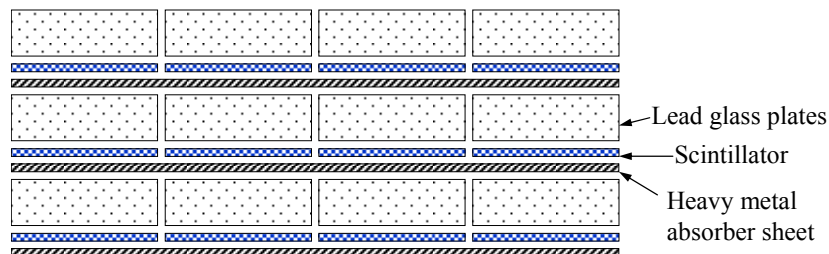


Fig. 2. The basic detector configuration.

The behavior and energy resolution of calorimeters constructed from scintillator plates readout by SiPM and passive absorbers have been studied extensively. Results of these studies can be used as a guide when we conduct our design studies. We will concentrate our effort on the Cherenkov detectors and their effects on compensation based on the dual readout scheme.

The properties of some common Cherenkov radiators are given in the Table 1. Lead glass is a common Cherenkov radiator that has been used in the electromagnetic calorimeters extensively in the past. Lead glass with PbO content as high as 80% with density as high as 6.2 g/cm^3 is commercially available. Such kind of lead glass will be an ideal Cherenkov radiator material for our design. Both the radiation length and the hadronic interaction lengths are reasonably short allowing us to design a very compact calorimeter. We expect only the first ~ 3 interaction lengths of the calorimeter are important for achieving compensation. Therefore after 3 radiation lengths, the dual readout will likely not be necessary and the lead glass can be replaced by regular heavy absorbers. The total volume of Cherenkov radiator required will be on the order of 100 m^3 .

Table 1. Properties of Cherenkov radiators.

Material	Density (g/cm^3)	Refractive Index n	Nuclear Interaction Length (cm)
Lucite	1.18	1.47	~ 70
Non-Leaded Cover Glass	2.5	1.52	~ 40
Medium-density lead glass	3.2 - 3.7	1.59	—
Medium-density lead glass	4.2	1.70	—
High-density lead glass	5.2 - 6.2	1.81-1.9	~ 25

The calorimeter will need to be divided into two sections, the EM section and the hadronic section. In general, segmentations in the EM section need to be finer than the segmentations in the hadron section. In principle, both can be constructed using the same Cherenkov and scintillation radiator sandwiched structure with somewhat different geometric parameters. We assume the thickness of lead glass plates is 2.5 cm for the hadron section in the following discussions.

The calorimeter configuration discussed above can also be used as hadron calorimeter only and the tungsten silicon or tungsten scintillator EM calorimeters can be placed in front of it. The EM calorimeter typically is about one interaction thick and a significant fraction of hadrons will

interact in it. Therefore, the EM calorimeter must also be able to compensate its different response to EM and hadron showers.

The Cherenkov radiator can also be made from Lucite in conjunction with high z metal such as tungsten and uranium. The Cherenkov light yield in Lucite will be about 50% lower compared to the light yield in high quality lead glass because of lower refraction of index and the spectrum response. With a much smaller sampling frequency, we expect the performance of the detector will be degraded somewhat if we choose this approach.

3. Cherenkov light yield

The yield of the Cherenkov light when a charged particle penetrates a piece of radiator is determined by the index of refraction of the radiator and the velocity β of the particle. The photon absorption in the radiator also plays a critical role. The Cherenkov photon yield as functions of β and the index of refraction in the wavelength range of 400 to 700 nm is shown in Fig. 3. For materials listed in Table 1, the light yield is 260 to 350 photons per centimeter or 650 to 875 photons for a 2.5 cm thick radiator plate if β approaches one.

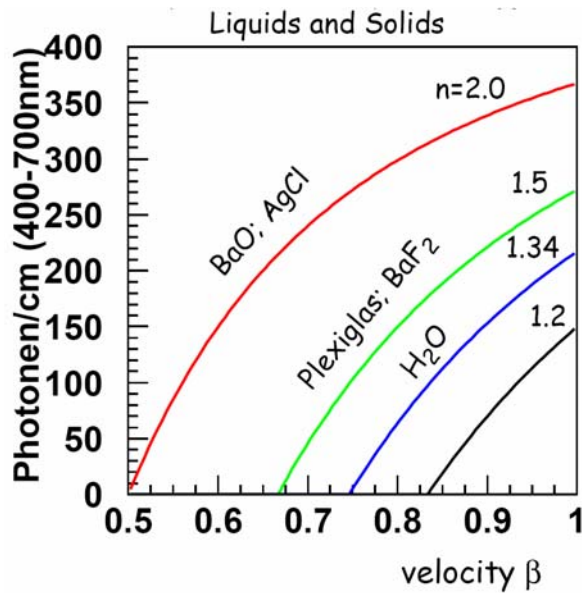


Fig. 3. Cherenkov light yield as a function of particle velocity and the index of refraction of the radiator.

The Cherenkov threshold β_{th} is given by

$$\beta_{th} = \frac{1}{n}$$

where n is the index of refraction of the radiator. As the Fig. 3 shows, the Cherenkov light yield increases with the particle velocity β and reaches a maximum when β approaches one.

4. Exploring the Cherenkov light

We plan to study two main effects of the Cherenkov light in the calorimeter.

(1) Compensation

Within showers produced by hadron jets, the Cherenkov light is mostly produced by the EM components of hadron showers. This is because the majority of electrons and positrons produced in showers mostly have β value very close to unity, whereas the majority of the hadrons produced in hadron showers have β value much less than one. Also, the total number of charged particles in a hadron shower with $\beta > \beta_{th}$ is much larger in EM showers than in the hadron showers of similar energy. The calorimeter compensation will be based on these phenomena. We need to study these effects in detail to find the best and the most economical detector configuration.

(2) Shower shape and separation

Because the hadron interaction length is much larger than the radiation length in detector media, an EM shower is concentrated in a much smaller volume compared to hadron showers that will have a much larger spatial spread. The charged particles that are capable of emitting Cherenkov light tend to be concentrated in the forward direction. The shower shape defined by the Cherenkov light in a Cherenkov radiator based calorimeter will be more compact than the shape defined by a scintillating light in a scintillator based calorimeter. The configuration of the calorimeter that we are proposing can take advantage of these phenomena.

In a calorimeter based on the PFA algorithm, separating the neutron clusters from the charged hadron cluster is very difficult because particle showers in the high energy hadron jets tend to overlap in the calorimeter. The fact that the showers measured from the Cherenkov light are much more compact can be used to help separating energy clusters caused by neutral and charged hadrons. Monte Carlo studies are needed in order to verify this speculation.

5. Cherenkov light readout

Both the plastic scintillator plates and the Cherenkov radiator plates are readout by using imbedded WLS fibers and SiPMs that are directly mounted on the plates in a similar fashion as used in other scintillator plate based calorimeters. A basic readout configuration is shown in Fig. 4 as an example.

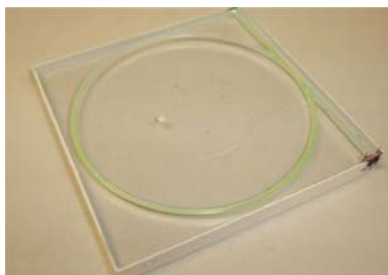


Fig. 4. WLS fiber readout for a scintillator plate with a SiPM mounted at the lower right corner. This photo was taken by the CALICE collaboration.

Here, we only discuss the Cherenkov light readout. Since the Cherenkov light yield is much lower than the scintillating light yield in plastic scintillators, maximizing the light collection efficiency is more important in order to collect sufficient amount of photoelectrons.

(1). Cherenkov light collection using WLS fiber

The photoelectron yield from Cherenkov light in a piece of lead glass readout by WLS fiber was studied at DESY for the design of the TESLA forward calorimeter [5]. As shown in Fig. 5, the lead glass strip used in this study has a cross-section 10 mm x 10 mm and the length is 4 cm. A 1 mm diameter WLS fiber was imbedded in a groove on the top surface of the lead glass strip. The lead glass was SF57 flint glass with an index of refraction ~ 1.8 . The WLS fiber was readout by a XP1911 PMT with an estimated average quantum efficiency of $15 \pm 2\%$. The number of photoelectrons observed by the PMT were measured by using spectrum hardened cosmic ray muons and the result obtained was 2.4 ± 0.5 photoelectrons per muon.

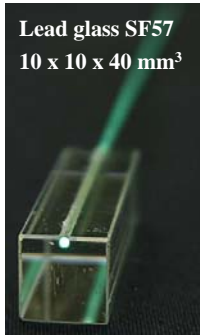


Fig 5. Lead glass strip with a imbedded WLS fiber.

Once the number of Cherenkov photons (N_γ) produced is known in a radiator block, the number of photoelectrons (PE) observed by a photon detector attached to one end of a WLS fiber imbedded in the Cherenkov radiator can be estimated by

$$PE = N_\gamma \eta_1 \eta_2 \eta_3 \eta_4$$

- η_1 : the probability of a photon hits the WLS fiber
- η_2 : the quantum efficiency of the WLS fiber
- η_3 : the light “trapping” efficiency of the WLS fiber
- η_4 : the quantum efficiency of the photon detector

The light collection efficiency of the WLS fiber η_1 can be enhanced by the multiple reflections of photons on the surface of the radiator block and can be much larger than the fraction of the aerial coverage by the WLS fiber. The quantum efficiency η_2 should be close to one if the wavelength of the photons is greater than the absorption limit of the WLS fiber. The trapping efficiency η_3 depends on the numerical aperture of the WLS fiber and is determined by the fiber manufacture. Typically it is between 4% and 10% if the wavelength shifted photons are readout from only one end of the fiber without considering the reflection from the other end. The quantum efficiency of the SiPM in ref. [1] made in Russia is about 15%, similar to the average quantum efficiency of the PMT used in the DESY study. This technology has made great progress since its invention

just a few years ago and will certainly improve further in near future. The quantum efficiency of the new SiPMs manufactured by Hamamatsu has already approached $\sim 30\%$ as reported in the 2005 ALCPG Snowmass workshop. Fig. 6 shows the photoelectron peaks by using a Hamamatsu prototype H100 SiPM. It demonstrates the remarkable capability of this new photon detector technology. With a 100 pixel device, photoelectron peaks up to 60 pe's are visible.

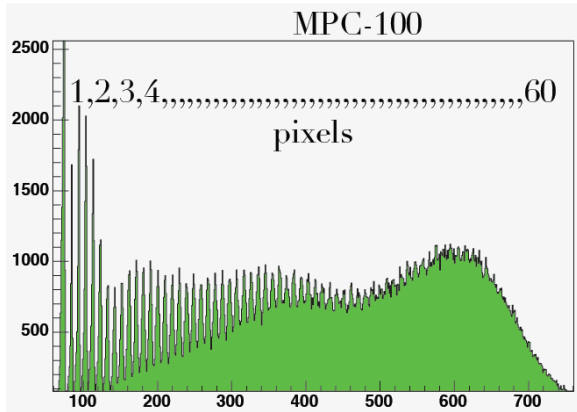


Fig. 6. Photoelectron spectrum obtained by a Hamamatsu H100 prototype silicon photomultiplier.

With square or rectangular Cherenkov radiator plate, we expect to lay the fibers on to the top surface in the direction of Cherenkov light cones to maximize the light collection efficiency. Depending on the size of the radiator, multiple turns or spiral shaped fiber arrangement can be considered. Fiber aerial coverage fraction in the range of 10% to 20% should be sufficient since the multiple light reflection will further improve the light collection. The light collection technique should be optimized by Monte Carlo simulation and tests.

We expect that the combined conversion efficiency from produced Cherenkov photons to photoelectrons can reach about 1% when the fiber size, the fiber aerial coverage and SiMP coupling, etc. are optimized. If we can achieve this level of conversion efficiency, the number of photoelectrons collected by a photon detector attached to one end of the fiber for a minimum ionizing particle with $\beta \sim 1$ penetrating a 2.5 cm thick high density lead glass will be between 6 and 9 if we use the radiator materials listed in Table 1. Based on this analysis, we expect that the number of photoelectrons will not be a limiting factor for achieving a reasonable energy resolution based on Cherenkov radiation with WLS fiber and SiPM readout.

(2). Directly collect Cherenkov light by SiPM

It is possible to consider mounting a SiPM directly on the top surface of the Cherenkov radiator without the WLS fiber if the size of the radiator is not too large. The active area of the current SiPM is only 1 mm^2 and the light collection will be quite low by using this method even we include the enhancement due to photon multiple reflections. However, we do not expect that the total number of photoelectrons collected in a shower to be the limiting factor determining the performance of the compensation as discussed above. The situation also will improve when larger active area SiPMs that are under development by industry become available.

Proposed Plan of Work

- Investigate the response and energy resolution of the scintillator and Cherenkov radiator hadron calorimeter. Optimize the detector design to accomplish the compensation.
- Investigate the performance of Particle Flow Algorithm of the hadron calorimeter using Cherenkov radiator. Optimize the detector granularity to accomplish the separation of showers induced by charged and neutral particles.
- Develop a conceptual design of a hadron calorimeter constructed from lead glass glass crystals and plastic scintillator plates.
- Determine the light yields of lead glass crystals read out with waveshifting fibers and/or with Silicon PM's as a function of crystal material, geometry and surface treatment.
- (If the initial studies demonstrate feasibility) Construct a prototype and demonstrate its performance in a test beam.

Broader Impact

This research direction of proposal, if funded will contribute to the knowledge base in our Physics Department. The beneficiaries of that will be postdocs and graduate students. If the research is successful, results will not only be useful to the future International Linear Collider, but also can be applied to other high energy particle physics experiments.

Results of Prior Research

The University of Washington group has been working on GEM based digital calorimeter in collaboration with the University of Texas at Arlington since 2004. We received funding from DOE through University of Oregon in 2005 to develop a DAQ system that supports the cosmic ray test of GEM chamber stack under construction at UTA. This work is progressing well. In recent years, the UW group has worked on a number of large detector development projects, including the ATLAS muon system design and construction, the D-zero forward muon system construction and the D-zero silicon microstrip detector tracking upgrade project for RunIIb. We have also worked in collaboration with IHEP in Beijing on developing a new type of RPC chambers for the muon detection. All these detector development projects were highly successful and have resulted a number of instrumentation papers in NIM and IEEE Transactions on Nuclear Science that are listed in the Biographical Sketch of the investigator of the University of Washington.

Dr. Adam Para of Fermilab has been doing ILC calorimeter related detector design studies and Monte Carlo simulations, in particular the PFA studies. Dr. Para has extensive experiences in calorimeter and muon detector development for high energy and neutrino physics experiments. He has authored a number of instrumentation papers on the subject of calorimeters based on high pressure gas and scintillators with WLS fiber readout in recently years.

Facilities, Equipment and Other Resources

The University of Washington Physics Department has a small electronics shop that can design electronics boards, etch and drill printed circuit boards. The Elementary Particle Experiment Group at UW has extensive history in HEP detector development, particularly in gas detector development and construction. Recently we have just completed a large detector construction project that involved building ~32,000 high precision drift tubes and 80 high precision chambers for the ATLAS forward muon system in our laboratory. We have a gas mixing system, some NIM, CAMAC and VME based readout electronics.

Our Physics Department machine shop is one of the largest physics department machine shops in the United States. We have available four CNC mills, two CNC lathes (turning centers), a wire EDN machine, the Dysecker, five conventional lathes and four conventional mills with digital readout. In addition, we have clean-room facilities with temperature control available. The machine shop is staffed with six experienced machinists and tool & dye makers. The joint work with mechanical engineering gives us access to the Department of Mechanical Engineering composite materials laboratory, which has available for our use a hot press and oven. We also have access to a larger oven in the Department of Material Sciences, which we used for fabrication of the D0 silicon vertex detector layer 0 installation tooling. The Physics Department machine shop provides facilities on a cost-sharing basis. The Physics Department contributes two-thirds of the cost on a cost-share basis for certain research projects.

FY2006 Project Activities and Deliverables

- Establish Monte Carlo models so that realizable and realistic results can be obtained.
- Perform initial calorimeter simulation and detector optimizing
- Perform small scale prototype tests and report the results in conferences.
- Investigating the source and quality of high density lead glass.

FY2007 Project Activities and Deliverables

- Perform detailed simulation to compare the performance of various detector configurations for compensation and cluster separation techniques.
- Continue prototype tests
- Submit paper(s) for conferences and instrumentation journals.

Budget justification for University of Washington

We request support for a post-doctoral associate who will perform Monte Carlo simulations to verify the design concept of the dual readout calorimeter described in this proposal and conduct small scale test to provide technical information for the design studies. We also request a small amount of funding for materials and supplies need for these studies and tests. The purpose of these tests will be providing technical information for general design studies.

Two year budget in then year K\$ for University of Washington

Item	FY2006	FY2007	Total
Other Professionals			
Post Doc (12 mos.)	\$43,008	\$44,316	\$87,324
Total Salaries and Wages	\$43,008	\$44,316	\$87,324
Fringe Benefits	\$9,978	\$10,281	\$20,259
Total Salaries, Wages and Fringe Benefits	\$52,986	\$54,597	\$107,583
Equipment	\$ -	\$ -	\$ -
Travel	\$2,000	\$2,000	\$4,000
Materials and Supplies			
Prototype Test Hardware	\$5,000	\$5,000	\$10,000
Total Direct Costs	\$59,986	\$61,597	\$121,583
Indirect Costs	\$30,517	\$31,411	\$61,928
Total Direct and Indirect Costs	\$90,503	\$93,008	\$183,511

Notes

Fringe Benefits calculated at 23.2% for PostDoc (research) staff

Indirect Cost of 55.5% applied to PostDoc salary/fringe benefits and travel

More collaborators

A number of Fermilab physicists have expressed interests in this project and may join in at a later stage. Also, the IHEP (Beijing), China and HEP group from the University of Science and Technology of China have expressed interests in participating.

References:

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