LC Detector R&D proposals from the 4th Concept

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1 Introduction

We have submitted three LCRD proposals to support three areas of work on new detectors within the 4th Concept, and are discussed in

- Sec. 2 (“Development of the 4th Concept Detector”)

Support for students and young physicists to work on 4th concept in all respects, but with an emphasis on the simulation and physics not only of 4th Concept, but also of cross-concept combinations of vertex-tracking-calorimeter-muon subsystems. All of the work evidenced in the report on “Physics and Simulation ...” has been supported on small funds, and this area of work, in addition to the work on new dual-readout designs, would be supported by these funds. Importantly, we have been simulating cross-concept detectors, such as the SBD pixel vertex detector, the LDC TPC, and the 4th calorimeter, and these studies will become of great importance as we approach two EDRs.

- Sec. 3 (“Development of New Methods and Conductors for Large Solenoids”)

An iron-free dual solenoid muon identification and reconstruction system in which the flux from the central tracker is returned by a second, outer solenoid is a new. This includes a proposal to study new superconducting conductors, solenoid designs and construction, and even high-$T_C$ conductors if appropriate.

- Sec. 4 (“Multiple Readout Calorimetry for the 4th Concept”)

Dual-readout and multiple-readout calorimetry is the complementary and distinguishing feature of 4th among the ILC concepts. Members of this concept have developed and beam tested new techniques in calorimetry that show promise for “utimate” hadronic energy resolution combined with absolute linear hadronic energy response in a calorimeter calibrated with electrons.

A fourth proposal for work on a new cluster-counting drift chamber that was presented and discussed at the Tracking Review at the Beijing meeting, Feb. 2007, and which is the tracking option in the 4th Concept DOD, was withdrawn since we made a mistake in thinking that F. Grancagnolo (INFN, Lecce) could be PI of an LCRD request. Thus, I think that this proposal is not active, in an LCRD funding sense, although we continue to work and simulate this option. EUDET and INFN funds are being requested.
2 Development of the 4th Concept Detector

Many of the activities of these three LCRD proposals involve people-intensive work such as simulations, design, fabrication of prototypes, etc. In addition to this, we have supported and wish to continue to support graduate students working on the 4th Concept. ¹ In addition, we have not previously been able to send even a single person important meetings, such as the TPC Jamboree in Aachen, due to limited discretionary travel funds, nor have we been able to have a collaboration-concept meeting except “accidentally” at Fermilab or CERN whenever it happened that a critical number of 4th concept participants were already present. Unlike GLD, LDC and SiD, the 4th concept is not supported by a national lab and as a consequence we have not had the flexibility that a lab allows for new projects.

The 4th Concept problems outlined in the areas of calorimetry, novel muon system and tracking have proceeded as fast as they have due to the coordinated work of a dozen or more young people and a half-dozen experienced physicists. The work of this proposal includes

1. An essentially complete simulation of the 4th detector now exists and the first physics problems have been solved ². Since 4th is so new in several respects, the optimization of particle identification (PID) will involve new techniques not yet implemented in the ILCRoot code. These are interesting and fascinating problems, but require time and effort by, we expect, young people.

2. Particle identification in a physics analysis is powerful, and we will continue to optimize the identification of all partons in this new detector (Sec. 4.3):
   
   • muon identification in a dual readout calorimeter is unique,
   • \((u, d, s)\) jets by jet reconstruction in the calorimeter,
   • impact parameter tagged \(c, b\) quarks and \(\tau\) lepton in the pixel vertex detector,
   • \(e\) and \(\gamma\) in the fiber or crystal calorimeter, and
   • the \(W, Z\) gauge bosons through \(jj\) calorimeter mass resolution in their di-jet decays)

are all interesting and critical problems that require intelligence and time, and they will be solved in the first year. At the moment, we have approximate functions for particle ID, but to achieve the best physics performance will require further work and optimization.

¹The totality of LCRD funds for 4th Concept to date are $10K from these LCRD general funds last year, and $30K from Fermilab for simulation and software work on SiD at Fermilab. Other funds have come from private university accounts and discretionary funds for travel.

3. We are simulating the pixel vertex detector of the SID concept within the 4th concept, and plan to further simulate cross-concept detectors, such as the SID silicon tracking with the 4th dual-readout calorimeters. This will enable us to directly compare a TPC and a silicon tracking system on physics events with everything else the same. This extraordinary capability may prove to be critical when the four concepts are narrowed to two EDRs, presumably by a series of marriages and swapping of detector subsystems. This has not been done before in high energy physics, but the ILCroot architecture allows these studies to be made, and these codes are available to all in the community. We take seriously the World Wide Study goal that an ILC detector must be two-to-ten times better than the LEP/SLC detectors, and therefore nothing less than the best detectors and ideas from each concept should be kept. It is clear than any one defined detector is a challenge to correctly and thoroughly simulate. Here we propose to go far beyond this.

4. These cross-concept simulations and studies are possible with the ILCroot simulation and analysis structure developed at Lecce and led by C. Gatto, and this in turn is only possible by the support of young students and their continuing support requested in this proposal. These problems are appropriate for masters degrees or beginning doctoral degrees.

5. Our functioning dual readout calorimeter simulation will be used to design the triple readout test beam module for which several critical issues must be resolved: how to measure the neutrons, what photo-converter to use, how to digitize the time history of the fibers, and how to maintain a constant volume sampling density in \(4\pi\) projective modules that can be assembled to maintain complete hermeticity and which are fully scalable. These are all people-intensive problems to be supported by the proposal.

6. The electromagnetic energy resolution of the DREAM module was limited by photo-electron statistics in the Cerenkov signal to \(\sigma/E = 25\%/\sqrt{E}\). (This also limited the estimate of EM fraction and therefore the hadronic energy resolution.) One way around this is more or larger diameter Cerenkov fibers. Another is to use a continuous scintillating crystal or glass with \(10^2\) times the Cerenkov light production. In this case we must be able to separate the scintillation and Cerenkov light to achieve dual readout, and this instrumentation has already started and the main work will be done in the calorimeter area, but the physics assessment will be done under this funding.

7. We need to assess the capabilities of SiPMs (silicon PMs, or Multi Pixel Photon Counters) with an eye on $/\text{mm}^2$ of the photocathode and dark rate. It may be that the new small Hamamatsu Ultra Bialkali PMT can be modified for use inside a magnetic field, and therefore the critical choice of photoconverter is not clear. The main hardware work will be done in the calorimeter area, including the digitizing
electronics under a separate request, but the scientific assessment and even the coordination and scientific direction of the work will be done here. The SiPM, should it prove adequate, will be used for both the fiber and the crystal calorimeters.

8. We will critically evaluate the addition of a forward tracking toroid\textsuperscript{3} just beyond the end of the TPC end caps and before the end cap calorimeter. We have allotted about one-half meter for tracking electronics here, but we can recover as much axial space as we like since the iron-free muon system is determined only by moveable coils. A toroid placed here gives a radial $p_T$ to an mainly axial track, and since the field of a toroid goes like $1/r$ and we can tailor the shape to be wider at smaller $r$, we can design the momentum resolution gain of the toroid to match the momentum resolution loss of the main tracker and recover good uniform forward tracking resolution. This is a very serious problem since the gain in tracking will be accompanied by a loss in both calorimeter pattern recognition and energy resolution. The trade-off will likely by physics process dependent, and therefore a very difficult problem to solve.

9. The main theme of the 4th Concept is multiply redundant and integrated measurements of all the bosons and fermions of the standard model. Therefore, coordinated work on all subsystems is required. There is almost no problem that involves a “factorizable” problem on a single subsystem that can be given to one isolated person or group. This funding request is essentially the glue that holds the rest together.

3 Development of New Methods and Conductors for Large Solenoids

We have proposed to only study the design and construction of superconducting (SC) solenoids based, initially, on the solenoids built at Novosibirsk. This study would include an assessment, or re-assessment, of high temperature SC (high-$T_C$) materials and other interesting possibilities such as $MgB_2$.

We have not proposed (but have suggested to Chris Damerell) that a series of three 5T solenoids be built for the beam tests of, in sequence, vertex chambers, tracking chamber prototypes, and tracking+calorimeter prototypes.

3.1 Novosibirsk work

Publications about coil design, presented at the 8th International Conference on Instrumentation for Colliding Beam Physics: Novosibirsk, Russia, February 28 – March 6, 2002

\textsuperscript{3}The problem of momentum resolution in the forward region of all concepts, and of all LEP detectors, was raised by Chris Damerell before the Tracking Review in Beijing, Feb. 2007. See talk by J. Hauptman at this meeting.

1. “Advances in superconducting magnets for high energy and astroparticle physics,” Yamamoto, Akira; Makida, Yasuhiro pp. 255-265


The CMS coil is much thicker than the Novosibirsk ones (0.8X0 for KEDR and 0.08X0 for CMD-2M), and so one question is the assessment of risk for a larger solenoid. The dual solenoids of the 4th concept need to be integrated with the detectors and also with the beam elements which themselves are intimately integrated with the detector. We define the several advantages to this dual solenoid system in our DOD, including precision measurement of muons, control of the field on and near the beam, some practical advantages of large consequence for push-pull like the ability to move easily and quickly, the ease of installation and re-installation, and also costs.

3.2 New conductors (MgB$_2$) and goal

Some colleagues on this proposal would like to explore the possibilities of new high-$T_C$, or at least higher $T_C$, conductors.\footnote{"Low-Temperature Superconductivity is Warming Up", P. Canfield and S. Bud’ko, Scientific American, April 2005, p. 81.}

We depend on two big solenoids for the new iron-free dual solenoid muon system and therefore have a direct interest in this work. It may be a long shot, but we do expect some definite progress by building upon the prior work at the Budker Institute in Novosibirsk (BINP).

4 Multiple Readout Calorimetry for the 4th Concept

Members of the 4th concept group have developed and beam tested so-called dual-readout calorimeters\cite{1, 2} that show promise for “ultimate” hadronic energy resolution combined with absolute linear hadronic energy response in a calorimeter calibrated with electrons. These are new and tested ideas in high energy physics and represent an orthogonal approach to PFA calorimetry.
This report contains results from extensive beam tests all of which are described in detail in the following five NIM papers (1-5) and the three drafts of NIM papers (6-8). The next two documents are 4th Concept papers defining the conceptual design of a full detector facility and its physics potential (9-10).

This report is organized as follows: in this section ("Introduction") we list our original accomplishments in this new area of calorimetry by both the DREAM collaboration and the implementation of these ideas by the 4th Concept group. In the section “Dual-readout Calorimetry: DREAM and 4th plans” we describe the research plans that will bring us to an ILC-capable calorimeter EDR by 2010 and backed up by substantial data on several systems. In the section “Current status of dual-readout calorimetry” we show the beam test data that support our R&D plans in the previous section, and that also define what we mean by dual readout. In the section “Physics and technology driven goals” we discuss performance goals, parton ID, front-end electronics, EMI and flyers, and mechanical issues of support of the solenoids which in turn support the calorimeter. Section 5 contains the R&D plans to reach a calorimeter EDR by 2010, and Sec. 6 contains the total budget that has supported dual readout work to date (by both DREAM and 4th) from all sources.


the following three papers are drafted for publication in *Nucl. Instrs. Meths.* and are based on the Nov-Dec 2006 beam test at CERN.


the following two papers are 4th Concept documents.


This document is the main definition of the configuration of the 4th Concept detector and is found on the WWS-OC website http://physics.uoregon.edu/ dhcpd/ wwsstudy/concepts/. Although over a year old, this DOD is mainly current with the exceptions of continual improvements in simulation and physics analysis (see next document), and other new ideas such as a forward toroid.


This document contains results on the physics capabilities of 4th, including the calorimeters through detailed simulations. This document is, naturally, continuously out of date as additions and improvements are made to the analysis. Not yet included are the dual-readout crystals and a comprehensive package to take advantage of particle identification in the dual-readout calorimeters and the iron-free muon system.
The NIM papers are products of the DREAM collaboration\textsuperscript{5} for beam tests in the H4 beam at CERN over the past four years. Current tests include the dual readout of scintillation and Čerenkov light in the continuous medium of a crystal or glass, the measurement of the time and energy dependence of the neutrons liberated from nuclei in hadronic showers, and tests of possible crystals or glasses that are better suited to dual-readout than PbWO\textsubscript{4} crystals. These papers represent about one paper per day of beam time. The DREAM group maintains substantial overlap of personnel but is independent of 4th Concept. The papers 1-10 are available at:

papers 1-8: http://www.phys.ttu.edu/dream and

http://highenergy.phys.ttu.edu under projects/drea/publications

dpaper 9: http://physics.uoregon.edu/lec/wwstudy/concepts/

dpaper 10: http://www.4thconcept.org

Numerous talks are available at the several ILC workshops with more recent results.

4.1 Dual-readout R&D: DREAM and 4th plans

We presently pursue three R&D projects described in Sec. 4.1.1 (improvements to the fiber DREAM module), Sec. 4.1.2 (readout of a single crystal or optical medium), and Sec. 4.1.3 (measurement of binding energy loss fluctuations).

The primary idea in 4th concept calorimetry is the dual-readout and multiple-readout of optical calorimeters to suppress the effects of fluctuations on energy resolution. These ideas have already been tested in the CERN H4 beam starting in 2003, but on small test modules, both fiber and crystal.\textsuperscript{6} Moving from the successful test module stage to a full-scale and scalable ILC module will require more funds.\textsuperscript{7}

For dual readout of Čerenkov and Scintillation light, there are five ways to separate the light signals:

1. by physically separate fibers (DREAM papers 1-5)

2. by direction, since Čerenkov light is propagated forward and scintillation light is isotropic (DREAM papers 5, 7 and 8);

3. by wavelength, since Čerenkov light is generated as $1/\lambda^2$ and scintillation light can be chosen by the fluor, but is usually in the green or red;


\textsuperscript{6}Supported by DoE Advanced Detector Research (ADR) program funds and on State of Texas funds, and later on LCRD funds\textsuperscript{[13]} which amounted to $10K.

\textsuperscript{7}The DREAM module cost about $150K and from this we estimate that a cubic-meter fiber module will cost about $500K. Since a cubic-meter beam module is \textit{grosso modo} about 1\% of a 4\pi ILC calorimeter, we estimate the 4th Concept fiber calorimeter at about $50M plus contingencies and dedicated electronics on the 20K channels.
4. by polarization, since Cerenkov light is polarized and scintillation light is not; and,

5. by time, since Cerenkov light is prompt and scintillation light has a decay lifetime given by the fluor (DREAM papers 5,8).

Methods (1) and (2) have been successfully tested on DREAM, and (2) and (5) successfully tested on PbWO$_4$ crystals in conjunction with DREAM. Method (4) has been calculated and seen weakly in DREAM data, but not published. Method (3) is easy and will be tested in the future.

Finally, it is apparent that dual-readout and it extensions and derivatives is an extremely rich area for innovation and also a route to “ultimate hadronic calorimetry” for the ILC[14]. We welcome participation from our colleagues in the ILC community in this proposal and its consequences.

4.1.1 Separate scintillation and Cerenkov Fibers: DREAM 1

The first proof-of-principle dual-readout module was the DREAM module tested in June 2003 from which the above papers were written. All objectives of this test were achieved, and results are discussed in Sec. 4.2.2.

The analysis of DREAM revealed that the Cerenkov photoelectron statistics were the limiting factor in the determination of the electromagnetic fraction, $f_{EM}$, each event and therefore the limiting factor in the hadronic energy resolution (beyond the lateral leakage fluctuations of about 4%).

Indeed, DREAM was equipped with two kinds of Cerenkov (i.e., clear) fibers, high-quality quartz from Polymicro (CMS HF calorimeter) in the central channels and clear plastic fibers in the outer channels that are a factor of 20 lower cost. The relative numerical apertures of these fibers resulted in 8pe/GeV light in the quartz fibers and 18pe/GeV in the plastic. One of the main goals of a new DREAM design is to increase the Cerenkov pe statistics to about 100pe/GeV by a combination of a higher fiber volume, higher numerical aperture and a higher quantum efficiency photoconverter. Building upon the DREAM measurements mostly presented in Sec. 4.2, we intend to

1. design a “scalable” fiber module that serves as a unit which can be replicated and stacked to make a large test beam module;

2. design a dual fiber arrangement with double-clad square fibers and a factor of two larger numerical aperture; and,

3. design a plug-on unit with SiPMs and associated electronics including the digitizer and readout. This unit will define the channel structure of the module, e.g., hexagonal or square channels.
4.1.2 Single crystal dual-readout: DREAM 2

The DREAM group has tested in the H4 beam (Oct-Nov 2006) the dual-readout of a single $PbWO_4$ and an array of 19 such crystals exposed to $e^-, \mu^-$ and $\pi^-$ beams at several energies and at many angles with respect to the beam to measure both the time and angular responses. Three papers (DREAM papers 6-8) are in draft. The motivation for a single crystal as opposed to a fiber is that the photoelectron yield will be huge even for the Čerenkov light, and therefore fluctuations in $pe$ counts will be negligible, however, the two kinds of light must be efficiently separated.

This will involve the likely use of SiPMs, dedicated FADCs, and some optical design to limit the number of SiPMs. The 4th Concept design has four crystals shadowing one fiber tower, and thus the crystals are about $2 \times 2$ cm$^2$ and number about 80K for a full system (Fig. 2). Our current status and results are given in Sec. 4.2.3 and our future R&D plans are roughly listed here:

1. find a crystal or glass better suited to dual-readout than $PbWO_4$ crystals, which are too fast, too luminous and too blue for good separation from Čerenkov light;

2. design a SiPM readout for a crystal using anywhere from one to four photoconverters per crystal[15]; and,

3. develop Čerenkov and scintillation light discriminators for dual readout by a combination of the methods in Sec. 4.1.

The main physics driver for crystal dual readout is to make better measurements of electrons and photons, and to maintain the ability to measure hadrons with high resolution. It is expected that this crystal calorimeter, backed up by the fiber module, will be able to measure very well the important decay $\tau \rightarrow \rho \nu_\tau \rightarrow \pi^\pm \pi^0 \nu_\tau$.

4.1.3 Binding energy loss fluctuations: neutrons by time history: DREAM 3

We knew immediately when DREAM achieved such good energy resolution in the beam in 2003 that the next largest fluctuation in a hadronic shower was the fluctuation in binding energy (BE) losses when hadrons break up and liberate neutrons from the heavy nuclei of the absorbing material. The hadronic energy used to break up the nuclei must overcome the BE and is lost, but it is correlated with the kinetic energy of the neutrons which, when liberated, are below 8 MeV and typically 2-3 MeV. These neutrons elastically scatter their way down to thermal energies over microseconds, but are measurable in a calorimeter medium down to tens of keV as they scatter protons in, say, the plastic scintillating fibers of DREAM.

This has been roughly measured in the DREAM module (during the same week of test beam for the crystal dual-readout test in Nov-Dec 2006) by driving the $\pi^-$ beam into one DREAM channel and reading out in time neighboring channels (DREAM paper 6).
The current status of neutron time history measurements are discussed in Sec. 4.2.4 and current and future R&D plans are the following:

1. test fibers with different Birks constants for neutron signal and efficiency (INFN, Messina and Trieste);

2. test DREAM module will FADC readout for spatial and time structure of MeV neutrons;

3. assess time history for 4th concept calorimetry; and,

4. design and study non-hydrogenous scintillating fibers as a neutron-blind medium for comparison with plastic scintillating fibers.

We want to also read the time history of the Čerenkov fibers as a baseline to all EM activity in the calorimeter at all times. This may be important when running at the ILC. This optical calorimeter is clearly fast enough for this task, maybe in 5-ns time buckets.

4.2 Current status of dual-readout calorimetry

The geometry of the 4th Concept is shown in Fig. 1 in which the calorimeters we discuss in the report are in yellow: the inner, or front, calorimeter is the dual-readout crystal about $2 \times 2 \times 25$ cm$^3$, and the outer deeper calorimeter is the dual-readout fiber calorimeter, slightly improved over DREAM, with a time history FADC readout of both fiber types.

It must be noted, as an aside, that 4th Concept is an integrated detector[12, 11] with a novel dual solenoid to return the magnetic flux, and a precision muon spectrometer that is coordinated with the dual-readout calorimeters. All calorimeter channels are projective, and the geometry of the basic unit is shown in Fig. 2 in which the dimensions are approximate and not critical for this discussion. An actual physics module might be, for example, a $5 \times 5$ of this unit.

The beam configurations in which all DREAM measurements were made is shown in Fig. 3(a). The beam sees the trigger counters and hodoscope, then the Pre-Shower Detector (PSD) consisting of 5mm of Pb followed by a scintillator. The distribution of this PSD to a an electron beam is shown in Fig. 3(b). Beyond DREAM is an additional $8 \lambda_I$ absorber followed by a large paddle scintillator used as a muon tag. The area directly in front of the DREAM module had a small platform which was used for several different purposes during the DREAM beam tests:

- this figure shows the Interaction Trigger Counter (ITC) directly behind 10cm of lucite (about 0.1 $\lambda_I$) and in front of DREAM. High multiplicities in the ITC are used to tag “interaction jets”;

- the absence of the lucite was used in single $e^-, \mu^-, \pi^-$ runs;

- a single $PbWO_4$ crystal on a rotating table was used to measure the angular dependence Čerenkov and scintillation light in these crystals;
Figure 1: The 4th detector showing final focus transport, the dual solenoids for iron-free flux return, the vertex and tracking systems, and the calorimeters in yellow: inner one is dual-readout crystal and outer is triple-readout fiber. The total depth is $10 \lambda_T$ and all calorimeter channels are projective with the origin.

- a larger array of 19 $PbWO_4$ crystals was configured with readout from both ends of the crystals was rotated in the beam that was directed both along and perpendicular to the crystal axis; and,

- Pb absorbers were placed in front of the crystals to allow measurement of the response of $PbWO_4$ to shower particles at different shower depths in both Čerenkov and Scintillation light.

All of these different configurations lead to fundamental calorimetric measurements by the DREAM collaboration and are characteristic of our systematic R&D approach to understanding and optimizing dual readout for detector purposes.

4.2.1 Scalable module

The next step is the design and construction of a “scalable” module about half the mass of DREAM that can be repeated and stacked to form a larger, several tonne beam-ready module. The basic module would be about five times the unit cell shown in Fig. 2, that is, about 20cm x 20cm front face and about 1.5m deep. This unit can be stacked around
Figure 2: The unit cell of the calorimeter showing the $4 \times 4 \text{cm}^2$ front face with four $2 \times 2 \text{cm}^2$ dual readout crystals. These four crystals match the 1-meter deep triple readout fiber calorimeter.

in azimuth and stagger stacked in $z$. This is approximately a hermetic and projective calorimeter.

4.2.2 Dual-readout fibers

We discuss the energy resolution and the response linearity, followed by our R& plan to improve on this performance.

Hadronic energy resolution The relative EM-to-hadronic responses for the separate Čerenkov and Scintillation calorimeters are approximately

$$\left( \frac{E}{h} \right)_C \equiv \eta_C \approx 5 \quad \text{and} \quad \left( \frac{E}{h} \right)_S \equiv \eta_S \approx 1.4$$

(1)
Figure 3: (a) The DREAM calorimeter setup in the CERN H4 beam; (b) Distribution of the PSD in an electron beam, clearly showing the capability of this simple counter to identify $\pi^-$ and $\mu^-$ (in coincidence with a MU signal), and also electrons, evidently after $e^- \rightarrow e^-\gamma \rightarrow e^-e^+e^-$ (“3 mips”), and a hint of 5 mips.
and the energy response of each calorimeter to incoming hadronic energy, $E$, can be written directly for the Čerenkov calorimeter as

$$C = [f_{EM} + \frac{1 - f_{EM}}{\eta_C}]E$$

(2)

and for the scintillation calorimeter as

$$S = [f_{EM} + \frac{1 - f_{EM}}{\eta_S}]E,$$

(3)

where $f_{EM}$ is the fraction of the shower that is electromagnetic. For example, a hadronic shower with only $\pi^\pm$ and no $\pi^0 \rightarrow \gamma\gamma$ would have $f_{EM} = 0$. The electromagnetic fraction, $f_{EM}$, can easily be seen in the data in Fig. 4 by writing Equ. (2) as

$$\frac{C}{E} = \frac{1}{\eta_C} + f_{EM}(1 - \frac{1}{\eta_C}),$$

and since $1/\eta_C \approx 0.2$, the Čerenkov signal for events with zero EM activity (that is, no $\pi^0$s produced, only $\pi^\pm$) should be 20% of the shower energy. This is seen directly in Fig. 4 where the $f_{EM}=0$ intercept is at 40 GeV out of 200 GeV, i.e., $C/E \approx 0.20$.

Therefore, the Čerenkov signal is well correlated with $f_{EM}$. For each beam event, $C$ and $S$ are measured, and the response functions in Equ. (2-3) are solved for $f_{EM}$ and $E_{shower}$, the best estimate of $E$. $f_{EM}$ is easily gotten from $C/S$ and shown in Fig. 5 for 100 GeV $\pi^-$ showers in DREAM. The shower energy can be calculated as $E_{shower}$ is

$$E_{shower} = \frac{\eta_S E_S (\eta_C - 1) - \eta_C E_C (\eta_S - 1)}{\eta_C - \eta_S}.$$  

(4)

In Fig. 6 we show a sequence of shower energy distributions for 200 GeV $\pi^-$. In Fig. 6(a) the distribution of the scintillation signal is shown with an rms of 14%. When the shower energy is calculated from Equ. 4 we get the distribution in Fig. 6(b). It would be as easy as that were it not for side leakage fluctuations in the 30-cm wide Cu DREAM module that we estimate at $\sim 4\%$ for hadronic showers. The shower energy, $E_{shower}$, solved for is too low and it fluctuates by $\sim 4\%$. In effect, the electromagnetic fraction calculated from Equ. (4.2.2) as

$$f_{EM} \approx \left(\frac{C}{E_{shower}} - \frac{1}{\eta_C}\right)(\frac{\eta_C}{\eta_C - 1})$$

fluctuates by 4% because the denominator $E_{shower}$ fluctuates by 4%. Using this estimate of $f_{EM}$ in Equ. (3), the energy resolution improves from 14% to

$$\sigma_E/E \approx 5.1\%$$  (called Q/S method in ref. [3]).
Figure 4: The mean Čerenkov pulse height vs. $f_{EM}$ for 200 GeV interaction jets. Notice that at $f_{EM}=0$, the Čerenkov signal is about 20%, that is, for zero electromagnetic activity in a hadronic shower, 20% of the Čerenkov light comes from $\pi^\pm, K^\pm$ and $p$. At $f_{EM}=1$, the Čerenkov signal is nearly the shower energy. [“Hadron and Jet Detecton with a Dual-Readout Calorimeter”, N. Akchurin, et al., Nucl. Instr. Meths. A537 (2005) 537-561.]

This estimate still includes lateral leakage fluctuations of $\sim 4\%$ from $f_{EM}$. However, in this beam test it is possible to make a better estimate of $f_{EM}$ each event by calculating $f_{EM}$ as

$$f_{em} \approx \left( \frac{C}{E_{beam}} - \frac{1}{\eta_C} \right) \left( \frac{\eta_C}{\eta_C - 1} \right)$$

This suppresses leakage fluctuations in the calculation of $f_{EM}$, leading to a an absolute lower limit on the energy resolution.
Figure 5: The distribution of the EM shower fraction, \( f_{EM} \), for 100 GeV \( \pi^- \) showers in DREAM. \( f_{EM} \) is calculated directly from the Q/S ratio, shown on the scale at the bottom of the figure. [“Hadron and Jet Detector with a Dual-Readout Calorimeter”, N. Akchurin, et al., Nucl. Instr. Meths. A537 (2005) 537-561.]

The DREAM module was a proof-of-principle test module: can the dual-readout of scintillation and Cerenkov light in the body of a hadronic shower succeed in measuring, and therefore confer the capability to suppress the large fluctuations in EM energy deposits that are spread throughout the widely fluctuating volume of a hadronic shower, for low energies (20 GeV) to high energies (300 GeV), and with what precision?

The DREAM module was never intended to set a record of any kind: not energy resolution for hadronic or EM particles, not robustness and ease of calibration, not hadronic or EM and response linearity, etc., although it did perform spectacularly well on all of these in
Figure 6: (a) The distribution of the scintillator (S) signal for 200 GeV $\pi^-$. This is the raw resolution that a typical scintillating sampling calorimeter would achieve; (b) the energy distribution calculated from Equs. 2-3 using only the S and C (Čerenkov) signals for each event. This result has leakage fluctuations of approximately 4% contributing to the resolution; and, (c) the energy distribution using the known beam energy (=200 GeV) to make a better estimate of $f_{EM}$ each event, thereby suppressing the effects of leakage fluctuations. These data are from “Hadron and Jet Detection with a Dual-Readout Calorimeter”, N. Akchurin, et al., *Nucl. Instr. Meths.* A537 (2005) 537-561.
addition to demonstrating conclusively the principle of dual-readout.\textsuperscript{8}

The energy dependence of the resolution for the two cases, Figs. 6(a) and 6(b), are shown in Figs. 7(a) and 7(b), respectively. Fits to these data yield

\[
\sigma_E/E = 64\%/\sqrt{E} \pm 0.6\% \quad \text{(with leakage fluctuations)}
\]

\[
\sigma_E/E = 19.2\% \pm 1.6\% \quad \text{(leakage suppressed using } E_{\text{beam}})\]

The former is clearly too pessimistic and dominated by leakage fluctuations of 4%; the latter is too optimistic since a fluctuating component has been replaced by a known constant. Reality for dual readout in a fiber calorimeter like DREAM lies somewhere between these two functions.

**Absolute energy calibration and hadronic response linearity** The suppression of the effects of \( \text{EM} \) fraction fluctuations in hadronic showers leads to a most important property of dual-readout calorimetry: the response of the calorimeter to hadrons is linear in hadronic energy, as seen in Fig. 8, having been calibrated on 40 GeV electrons into the centers of each channel. Thus, the energy scale of the DREAM calorimeter is \( \text{EM} \) energy. The shower energy estimates in Fig. 8 use only the Čerenkov and Scintillation signals and not the beam energy, and therefore correspond to the distribution in Fig. 6(b).

This linearity is physically not surprising since the volume of the DREAM module is uniformly and densely sampled with optical fibers which themselves are excellent optical conduits that pipe the optical photons out to PMTs at the rear of the module. Although built with some care, the module was not subject to the degree quality control that would be imposed for an experiment. For example, on the edges of the module are some broken fibers, and there may be such fibers in the interior that would contribute to a constant term. The measured constant terms of 0.6\% and 1.6\% are comfortably small in the absence of quality control.

**Strategy to improve on DREAM** The clear (Čerenkov) quartz fibers of DREAM were chosen for convenience and because they were available, but to reduce costs for this module built on a small budget, the outer ring of 12 channels was fitted with plastic fibers instead of the factor of 20 more expensive quartz fibers. The plastic fibers have a numerical aperture of 0.50 (yielding 18 \( \text{pe}/\text{GeV} \)) compared to 0.33 (8 \( \text{pe}/\text{GeV} \)) for the quartz.\textsuperscript{9} Inside each hole there were 4 Čerenkov fibers and 3 scintillating fibers. The quartz fibers with 8 \( \text{pe}/\text{GeV} \) contributed \( \sigma/E = 35\%/\sqrt{E} \) to the energy resolution of electrons, and a similar uncertainty in \( f_{EM} \) in hadronic showers, thereby limiting the hadronic energy resolution.

\textsuperscript{8}Therefore, it is somewhat disingenuous to claim that DREAM is deficient in some respect, e.g. EM resolution, when it was never intended to be so.

\textsuperscript{9}The numerical aperture is related to the capture cone angle \( \theta \) as \( NA = \sin \theta \).
Figure 7: (a) The DREAM energy resolution using on the Čerenkov and Scintillation signals that is dominated by the 4% lateral leakage fluctuations; and, (b) the DREAM energy resolution for \( f_{EM} \) calculated each event as \( f_{EM} \approx (C/E_{beam} - 1/\eta_C)(\eta_C/\eta_C - 1) \). This is the best that a dual readout calorimeter like DREAM can achieve but without leakage.
Figure 8: The hadronic response of the DREAM module to \( \pi^- \) and "interaction jets" from 20 to 300 GeV using the \( Q/S \) method to correct each event to \( e/h = 1 \), i.e., using only the \( Q \) and \( S \) signals each event. See [3] for further details. These data are from “Hadron and Jet Detecton with a Dual-Readout Calorimeter”, N. Akchurin, et al., *Nucl. Instr. Meths.* A537 (2005) 537-561.

We will design for 100 pe/GeV in the ILC module, and this is accomplished by a combination of larger Čerenkov fiber volume, larger numerical aperture, and a photoconverter with higher QE such as a SiPM.

This limitation in the Čerenkov signal is evident in Fig. 9 in which the Scintillation signal resolution is far better than the Čerenkov signal resolution. A better “balanced” calorimeter would have equal EM resolutions for Čerenkov and Scintillation fibers.
Figure 9: Electron energy resolution for Scintillation and Čerenkov fibers, separately. This demonstrates the limitation of the Čerenkov signal due to low pe statistics relative to the scintillation pe statistics.

4.2.3 Dual-readout front-end crystals

As shown in Fig. 2 four crystals shadow the fiber calorimeter. We are characterizing single crystals (in this case PbWO$_4$) in $e^-$, $\pi^-$ and $\mu^-$ beams. The orientation of the crystal relative to the beam is shown in Fig. 10. A charged particle, or particles, passing through this crystal will generate Scintillation light that will reach the left ($L$) and the right ($R$) ends with equal intensity in the absence of absorption. The Čerenkov light generated will preferentially illuminate $L$, and reach a maximum when the complement of $\theta$ equals the Čerenkov angle, $\pi - \theta_C \approx 63^\circ$. For a thorough description[10], see DREAM paper 8. The measured angular dependence for 10 GeV $e^-$, solid red circles in Fig. 11, shows a marked angular dependence with a peak position expected by the Čerenkov angle, and also reveals that the light inside a PbWO$_4$ crystal contains several percent Čerenkov light.$^{10}$

$^{10}$This obvious fact has consequences for the calibration of PbWO$_4$ crystals with cosmic muons, for example.
<table>
<thead>
<tr>
<th>Calorimeter</th>
<th>a(%)</th>
<th>b(%)</th>
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<tr>
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<td>7</td>
</tr>
<tr>
<td>Sampling Scintillation fibers only</td>
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<td>2.2</td>
</tr>
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<td>&quot;Q/S&quot; method: use only Čerenkov and Scintillation</td>
<td>64</td>
<td>0.6</td>
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<tr>
<td>↓ Subtract out leakage fluctuations (4%)</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>↓ Subtract out Čerenkov pe fluctuations (35%/√E)</td>
<td>36</td>
<td>-</td>
</tr>
<tr>
<td>ZEUS hadron calorimeter (compensating, Wigmans)</td>
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<td>2.0</td>
</tr>
<tr>
<td>FLUKA simulations (jet reco energy)</td>
<td>36</td>
<td>–</td>
</tr>
<tr>
<td>FLUKA simulations (calor. energy)</td>
<td>30</td>
<td>–</td>
</tr>
<tr>
<td>↑ Add in &quot;jet reco&quot; fluctuations (2-3%)</td>
<td>38</td>
<td>-</td>
</tr>
<tr>
<td>↑ Add in E&lt;sub&gt;shower&lt;/sub&gt; fluctuations (30%/√E ?)</td>
<td>36</td>
<td>-</td>
</tr>
<tr>
<td>(f_{EM} \propto (C/Ebeam - 1/\eta_C))</td>
<td>19.2</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Table 1: Measurements (boldface) and estimates (italics) of the stochastic and the constant terms in the energy resolution of the DREAM dual readout calorimeter, including guesses about its extensions to triple readout. These are all derived from the beam test data of the DREAM module and described in the DREAM papers (1-3). We write the overall resolution as \(\sigma_E/E = a/\sqrt{E} \oplus b\).
Figure 10: A single PbWO$_4$ crystal in the beam after the tirggers counters and the definition of L, R and $\theta$.

The solid black triangular points in Fig. 11 are a measurement of this asymmetry for $e^\pm$ showers somewhat downstream of em shower maximum, at 7-9 $X_0$, in which the asymmetry is smaller since a large fraction of the charged particles are moving in random directions.\textsuperscript{11} The distribution of the asymmetry for 10 GeV $e^-$ (without brick) is shown in Fig. 12. The fraction of Čerenkov light is measured to be $14.8 \pm 6.1\%$. An independent Čerenkov -Scintillation discriminant is time, and the PMT pulse heights for both L and R, and at $\theta = \pm 30^0$ are shown in Fig. 13. The differences clearly show the fast and prompt Čerenkov light pulse.$^\text{12}$

The single crystal measurements were followed by an array of 19 PbWO$_4$ that we also rotated with respect to the beam as shown in Figs. ??(c) and ??(d), including $90^0$. The

\textsuperscript{11}We could not rotate the heavy Pb brick beyond $25^0$ because the remote rotor motor in the beam was too small. This test was done on essentially zero funds.

\textsuperscript{12}It must be remarked that the PMTs were not selected for speed, nor is PbWO$_4$ a suitable crystal for this purpose. Both PMTs and crystals were free or borrowed.
Figure 11: The L-R asymmetry measured in a PbWO₄ crystal for incident 10 GeV electrons for two shower depths: 0-3X₀ and 7-10X₀ by means of a Pb absorber in front of the crystal.

array was readout from both sides, Fig. ??(a), and the measured PbWO₄ Scintillation decay time constant was measured and is shown in Fig. ??(b).

The time distribution of the signals from this array exposed to 50 GeV e⁻ (left frames) and 50 GeV π⁻ (right frames), and the difference signals for both species, show the prompt Čerenkov pulse, Fig. 15.

The first attempt to put a crystal dual readout module in front of the DREAM fiber dual readout module and to measure the correlation between forward-backward asymmetry in the crystal and the fEM measured in the fiber module is shown in Fig. 16. The C/S signal ratio in DREAM is shown at the top of the plot from which fEM is calculated. We find a physical correlation.

We will pursue these tests in June 2007 with other crystals. The PbWO₄ crystals were used only because there were freely available and in common use. However, PbWO₄ might be nearly the worst crystal to use for purposes of dual readout: it is too fast, too luminous, and too blue. For easier separation of Čerenkov light, one would want a slower scintillator with less light (comparable to the Čerenkov luminosity), and scintillating further in the red to not overlap with the predominantly blue Čerenkov light.
Figure 12: The distribution of the L-R asymmetry for 10 GeV electrons traversing the crystal at $\theta = 30^\circ$. The mean asymmetry of 0.08 implies that total light generated in the PbWO$_4$ crystals is $14.8 \pm 6.1\%$ Čerenkov light.

4.2.4 Neutrons and beam losses: time history readout

A GEANT3 calculation of the correlation between the energy of neutrons liberated in a 100 GeV $\pi^-$ shower and the number of photoelectrons (pe) detected after 10 ns in the scintillating fibers of DREAM is shown in Fig. 17(a). The time history of protons (actually proton pathlength) and the time history of neutron pathlength in Fig. 17(b) shows that neutrons persist out to and beyond 100 ns. This is a comfortable time interval at the ILC with a beam crossing interval of $\sim 330$ ns.

We have proposed four methods to measure the neutron content in hadronic showers in our DOD[11] and here we show time history measurements made in the DREAM module in a preliminary test. Further beam tests will be made in mid-June where we hope to have time readout in whole rings of channels, rather than single channels.

An MeV neutron has a velocity $v \sim 0.05c$ and diffuses by elastic scattering out from a cylindrical source. An estimate of the time to active a neighboring channel at 7.2 cm is about 20 ns. The $\pi^-$ beam was driven into channel (tower) “T11” at the edge of the module, and the successively distant channels 3, 1 and 6 readout as shown in Fig. 18(a). The (inverted) PMT pulses in Fig. 18 show the expected behaviors: the Čerenkov pulses are faster than the Scintillation pulses, and the Scintillation pulses are later for T3 than for T11.

An analysis of the time history of the scintillating fibers shows a long-time tail in Fig. 19(b) with an e-folding time of about 20 ns that is absent in the Čerenkov fibers, Fig. 19(a).
Figure 13: The time structure of the signals measured in the left (L) and right (R) PMTs for 10 GeV incident electrons at $\theta = \pm 30^\circ$. The upper frames show the difference signal which is essentially the prompt Čerenkov light signal.

Integrating and plotting this late signal yields the neutron contribution to the scintillation signal, Fig. 19, of about 20-30%.

We will further study (experimentally) the time history readout for neutrons in hadronic showers, and also pursue FLUKA simulations. This is clearly not easy, but also possible. Of the other three techniques we have outlined in the DOD, none are so direct as the time history.

A further advantage to time history (of both Scintillation and Čerenkov) is that the calorimeter volume is continuously interrogated for signal, and with the intrinsic particle identification of the dual-readout calorimeter, we can monitor for stray bunches, flyers, inter-bunch and out of time particles, etc.

4.3 Physics, Particle Identification and technology goals

In the “Guidelines for Participating Groups” on 10 March 2007 from Wolfgang Lohmann, a list of goals is given. We have answered most of these in the preceding sections, some do not apply to an optical calorimeter (e.g., pulsed power and cooling), and others are best answered with ILCroot, the 4th simulation code.[17] We start at the top of this list, and at the end of this section we will note those items we have not yet had time to address.
Figure 14: (a) Drawing of the 19 $PbWO_4$ array showing PMT location on one side. A similar cone and PMT readout the other side; (b) Time dependence of the light from 50 GeV electrons into the $PbWO_4$ array; (c) The $PbWO_4$ array at zero degrees in the beam; and, at 30 degrees in the beam.
Figure 15: The time dependence of the PWO array signal for electrons and pions at 50 GeV. The upper frames show the time difference at the two angles $\theta = 0$ and $\theta = 30$ degrees.

Physics driven performance goals Foremost is jet energy resolution of $\sigma_E/E = 30%/\sqrt{E}$, about 1/2 LEP numbers, which when combined with good jet reconstruction leads to $W \rightarrow jj$ and $Z \rightarrow jj$ mass resolutions near 4-5 GeV/c$^2$.

A further important goal is the hermeticity of the calorimeter both near the beam ($\theta_{\text{min}} = 5$ mrad) and over $4\pi$. These problems we have “solved in GEANT” and in fact we intend to deal directly and early with these issues in the design and construction of the “scalable” module, described in Sec. 4.2.1.

The energy and angular resolutions on a jet are shown in Fig. 20 and the resulting $jj$ mass resolution after jet reconstruction in the 4th detector is shown in Fig. 21. These resolutions are quite good, but not yet final for 4th. We have the fiber calorimeter improvements, crystal dual readout, and neutron measurements (described in Sec. 4.1) yet to fully implement in the simulation.

Extensive beam tests of the DREAM dual-readout module have demonstrated that this technology is robust, inexpensive, maintains excellent energy resolution, is optical and therefore fast, is linear in hadronic energy (tested from 20-300 GeV) can be augmented to
“triple-readout” by measuring the MeV neutrons, and possesses unique particle identification capabilities. Salient and unique features of dual and triple readout calorimetry that are relevant to the following physics sections are

1. the energy scale is defined by electrons at a single energy (at 40 GeV in the DREAM tests);
2. electromagnetic energy (whether from $e$, $\gamma$, or radiative $\mu \to \mu\gamma$) is measured with equal Scintillation and Čerenkov response;
3. hadronic energy deposits have widely fluctuating fractions of Scintillation and Čerenkov both channel-to-channel and shower-to-shower;
4. a non-interacting track from the origin will leave a zero Čerenkov signal in the calorimeter since the Čerenkov angle is larger than the capture angle of the fiber;
5. the jet reconstruction has a high efficiency near $97\%$
Figure 17: For 100 GeV $\pi^-$ generated in GEANT3, the summed neutron kinetic energy at the time of neutron production is shown on the x-axis vs. the scintillator signal in $pe$ units summed after 10 ns on the y-axis; and, (b) the time distribution of the proton path length (upper frame) and the time distribution of the neutron path length (lower frame).
Figure 18: (a) The 100 GeV $\pi^+$ beam is sent into channel 11; and, (b) PMT pulse heights (inverted) for Čerenkov and Scintillation and for channels 11 and 3.
Figure 19: The time structure of the PMT signals for (a) Čerenkov and (b) Scintillation channels of tower 11. The clear 20 ns tail in the Scintillation signals is, we believe, the neutron signal that is necessarily absent in the Čerenkov signal since the MeV protons from $np \rightarrow np$ are far below Čerenkov threshold. The lower figure shows estimates of the neutron content of these 100 GeV hadronic showers as a function of the distance from the shower axis (in units of Moliere radii), and it is seen that the neutron signal is 20-30% of the signal in late Scintillation light.
Figure 20: The energy and angular resolutions calculated in the ILCroot simulations of 4th for \(e^+e^- \rightarrow H^0Z^0 \rightarrow c\bar{c}\nu\nu\) events at \(E_{cm} = 350\) GeV and \(M_H = 140\) GeV/c².

6. The crystal readout crystals with \(2 \times 2\) cm² segmentation can separate photons from a \(\pi^0\) up to about \(p_{\pi^0} \sim 10\) GeV.

The main physics goal of the 4th concept is to reconstruct and measure all partons of the standard model to a precision 2-10 times better than the already excellent LEP and SLD detectors by introducing new instruments into an integrated facility design. For this review, we concentrate on just the calorimetric measurements of jets (j), electrons (\(e^{\pm}\)), muons (\(\mu^{\pm}\)), individual hadrons (\(\pi^{\pm},\pi^0 \rightarrow \gamma\gamma,p,n,K,\text{etc.}\)), and fundamental bosons, the photon (\(\gamma\)), \(W^{\pm} \rightarrow jj\), and \(Z^0 \rightarrow jj\).

The dual-readout calorimeter offers spectacular and new capabilities in particle identification of muons, electrons and photons, and also provides a measure “hadronic-ness” in the showers of hadrons and jets. We have not yet exploited the full range of particle identification, but start by showing a simple scatter plot of Čerenkov signal vs. Scintillation signal for \(e,\mu\) and \(\pi\) as calculated in the ILCroot simulation in Fig. 22.
Figure 21: The mass resolution of two jets calculated in the ILCroot simulations of 4th for $e^+e^- \rightarrow H^0 Z^0 \rightarrow c\bar{c} \nu \nu$ events at $E_{cm} = 350$ GeV and $M_H = 140$ GeV/c^2.

4.3.1 Jets (uds) and hadrons ($\pi, K, p$)

The charged tracks of a jet are apparent in the tracker, and the total energy of the jet is measured in the calorimeter after clustering of the towers (both crystal and fiber) and the reconstruction of lower momentum charged tracks that have bent through large angles. Hadronic energies are characterized by fluctuations in the EM fraction not only jet-to-jet, but also channel-to-channel within a jet. We define the rms of this variation in the usual way

$$\sigma_{EM}^2 = \frac{1}{N} \sum_{i=1}^{N} [(f_{EM, i} - \bar{f}_{EM})^2].$$

A nearly equivalent statistic is the channel-to-channel mean-square difference of $C$ and $S$,

$$\sigma_{C-S}^2 = \frac{1}{N} \sum_{i=1}^{N} [C_i - S_i]^2.$$

Hadronic interactions result in the liberation of spallation neutrons from the breakup of absorber nuclei. In DREAM we have measured these neutrons with a mean-free-path of
Figure 22: Simple plot of Čerenkov signal vs. Scintillation signal for e, μ and π from ILCroot simulation.

about 15cms and this MeV-energy “neutron gas” will fill about one m³ falling off exponentially with distance from the shower axis. Typically, about 30-40% of the non-EM energy is carried by these multi-MeV neutrons which are measured by their elastic scatters on protons in the plastic scintillating fibers. Denote this neutron energy as $E_n$ and the fractional neutron energy as

$$f_n = \frac{E_n}{E_{shower}}$$

Therefore, a jet is defined as

**jet identification:**
- (a) multiparticle,
- (b) broad in angle and channel space,
- (c) $\sigma f_{EM} \gg 0$, and
- (d) $f_n \gg 0$.

A single hadron such as a $\pi^\pm$ from $\tau \rightarrow \pi \nu_\tau$ or $\tau \rightarrow \rho \nu_\tau \rightarrow \pi \pi^0 \nu_\tau$ decay is identified in the tracking as a single track with the characteristics of a hadronic shower in the calorimeter,
single hadron identification:
(a) single particle,
(b) broad in calorimeter channels,
(c) $\sigma_{fEM} >> 0$, and
(d) $f_n >> 0$.

4.3.2 $b, c$ jets and $\tau$ leptons

These particles with finite lifetimes and flight paths are first tagged in the pixel vertex chamber, and subsequently as $u, d$ jets and single hadrons, with or without a lepton ($e, \mu$).

4.3.3 Electrons ($e$) and photons ($\gamma$)

The response to EM energy is the same is the C and S fibers (and with similar resolutions with more Čerenkov $pe$/GeV) and therefore a electron is identified as

 electron identification:
(a) single particle,
(b) narrow in channel space,
(c) $C \approx S$,
(d) $\sigma_{fEM} \approx 0$, and
(e) $f_n \approx 0$.

A photon is aligned with the channel structure of the crystal dual-readout channels, so

 photon identification:
(a) absence of track,
(b) very narrow in crystals,
(c) $C \approx S$,
(d) $\sigma_{fEM} \approx 0$, and
(e) $f_n \approx 0$.

4.3.4 Muons ($\mu$)

A muon is measured first as a single (usually isolated if from a weak boson decay) track that is spatially matched to deposits in the calorimeter, and in turn matched to a track emerging from the rear of the calorimeter into the tracking muon spectrometer.\(^\text{13}\) Therefore, a muon is momentum measured to $\sigma_p/p^2 \sim 4 \times 10^{-5}$ (GeV/c)^{-1}, any energy loss within the calorimeter volume is measured to $\sigma_E/E \sim 0.2/\sqrt{E}$, and its momentum again measured in the annulus between the dual solenoids to $\sigma_p/p^2 \sim 4 \times 10^{-4}$ (GeV/c)^{-1}. For a 100

\(^\text{13}\)Achieved with the Kalman filter in ILCroot.
GeV muon with a 20 GeV radiation, each term is measured to about 1%, and therefore an emerging punch-through particle can be rejected relative to muons by a factor of 10-20. 

In addition, the dual-readout calorimeter alone uniquely identifies isolated $\mu^\pm$ and discriminates against $\pi^\pm$ with probabilities ranging from $10^{-2}$ to $10^{-4}$. This is unique to dual readout calorimetry and derives from the circumstance that the Čerenkov light from a single, nearly-aligned track yields zero Čerenkov pe since the Čerenkov angle is larger than the capture angle of the fiber. The scintillation fibers collect light equally from both the muon $dE/dx$ and EM radiative processes. The difference $(S-C)$ is therefore just the $dE/dx$ of the muon, which in dream was 1.1 GeV, shown in Fig. 23. Therefore, an isolated muon is identified as

isolated muon identification:
(a) single track,
(b) narrow in channel space,
(c) $\sigma_{f_{EM}} \approx 0$, (d) $(S - C) \approx 1$ GeV and $(S + C)/2$ much less than muon momentum, and
(e) $f_n \approx 0$.

The important problem of a non-isolated muon, such as in the center of a b-jet, has not been solved yet in 4th.

4.3.5 $W \rightarrow jj$ and $Z \rightarrow jj$ bosons

Both jets must satisfy the jet ID selections, including the $f_{EM}$ fluctuations in both jets. The $W \rightarrow jj$ and $Z \rightarrow jj$ mass resolutions from dream data using the beam momentum to calculate $f_{EM}$ are shown in Fig. 24. This is the optimum for a dual readout calorimeter like dream.

$W,Z \rightarrow jj$ identification:
(a) two jets, each multiparticle,
(b) broad in angle and channel space,
(c) $\sigma_{f_{EM}} >> 0$ for both jets,
(d) $F_n >> 0$ for both jets, and (e) $M_{jj}$ consistent with $M_W$ or $M_Z$.

The dual-readout capabilities in energy resolution and hadronic response linearity are matched by the parton identification capabilities. Figs. 26 and 25 are ILCroot generated $H^0 Z^0 \rightarrow b\bar{b}jj$ events in which the jets, even the narrow jet at the top of one event, is obviously and unambiguously hadronic since the EM fraction, or roughly $(S-C)$, fluctuates channel-to-channel, in addition to $f_{EM}$ differing from 1. This powerful identification capability is unique to dual-readout calorimetry, and the addition of neutron content information will only strengthen this capability.
Figure 23: Plot of (S-C) vs. (S+C)/2 for 40 GeV muons (left, top) and 20 GeV pions (right, top) and 200 GeV muons (left, bottom) and 200 GeV pions (right, bottom). At 20 GeV, the rejection of pions against muon is at least $10^2$; at 200 GeV it is at least $10^4$, and likely higher since the pion run had decay muon contamination.

4.3.6 Before and after the calorimeter (tracking and muon)
The tracking before the calorimeter is assumed here to be largely independent of the calorimeter performance, except for the pattern recognition that is necessary to associate
Figure 24: The 2-jet mass distributions for both $W \rightarrow jj$ and $Z \rightarrow jj$ decays superposed. This is the best a dual-readout module can deliver, and represents the ideal case of zero hadronic shower leakage. The final mass resolution of a dual readout calorimeter at the W mass will be worse than this, but we do not know by how much.

low momentum tracks with calorimeter showers. This association is rather mild in character, and we refer to it as lower-case “pfa” to distinguish it from the critical “PFA” algorithms that are essential in all respects for the PFA calorimeters for GLD, LDC and SiD. The muon spectrometer after the calorimeter and in the annulus between the two
Figure 25: The remarkable parton ID of the dual readout calorimeter is shown in even a single event. This \( H^0 Z^0 \rightarrow b\bar{b}jj \) event shows clearly that the narrow shower at the top is hadronic because of the obvious fluctuations in \( f_{EM} \) channel-to-channel. The other jets are also obviously hadronic. This is only the dual-readout; the addition of independent neutron measurements on reconstructed objects will only further discriminate between hadrons, EM objects and muons.

solenoids measures muon momenta to about

\[
\sigma_p/p^2 \approx 5 \times 10^{-4} (\text{GeV}/c)^{-1}
\]
Figure 26: A second $H^0Z^0 \rightarrow b\bar{b}jj$ event.

and this resolution is well-match to the energy resolution on radiative energy deposits within the volume of the calorimeter,

$$\sigma_E/E \approx 0.20/\sqrt{E}$$

both of which must match the muon track measured in the central tracking system.
4.3.7  Photo-converters, front-end electronics, DAQ and cable ways

The lights generated in the S and C fibers are transported to the rear of the module. In
DREAM, the fibers were bundled and put up against a PMT. In 4th, we are designing
an optical system, possibly a light mixer box, that will gather light and deliver it to a
SiPM.[16] The SiPM is followed by a FADC to digitize both S and C signals at about
200-400 MHz. It is expected that we can put all the optics and electronics on one unit that
plugs directly onto the fibers of one physical channel.

There is plenty of room between the back of the calorimeter and the solenoid since the
projective modules are of equal depth and at larger z a module extends less radially.

4.3.8  Geometry and mechanical support of scalable modules

The modules that we propose to construct with LCRD funds will be less massive than the
1-tonne DREAM module. The unit cell is a “truncated pyramid” geometry which can be
exactly stacked around the barrel in azimuth, and stagger-stacked axially. This has been
done in the geometry of GEANT4[12]. The overall geometry is shown in Fig. 27 with the
GEANT4 calorimeter and the dimensions used in the structural calculations.

It should be noted that these scalable modules are not delicate. The exterior is brass
all around; the fibers are confined to the interior of the module and only exit the module
at the read where the photo-converters and electronics are positioned. We expect that the
SiPM, FE, FADC are compact and mounted directly onto the fibers. There is sufficient
radial access for the cable-way to the end of the solenoid for signal extraction.

The support of the two solenoids has been conceptually engineered by Bob Wands
(Fermilab)[18] and shown in Fig. 28. Radial rods between the inner and outer solenoids
provide the main support, and an analysis of solenoid distortions is also show: an analysis
of vertical displacements (Fig. 29 and axial stresses primarily on the ends of the inner
solenoid (Fig. 30. The vibrational modes of this structure are shown in Fig. 31. This first
analysis of a dual solenoid magnetic configuration for a high energy detector revealed too
high stresses on the inner solenoid and since these stresses are lessened as 1/z, we have
moved the end coils out in z. There seem to be no show-stoppers.

An engineering support analysis for the fiber calorimeter inside the solenoid was made
by Zhijing Tang (Fermilab)[19] for the geometry in Fig. 27. Support rings on the scalable
modules of the barrel are shown in Fig. 32(a) and on the end caps in Fig. 32(b). The
main cradle support for the barrel part of the calorimeter is shown in Fig. 32(c), and the
main structural support for the end caps is shown in Fig. 32(d).

One of the main goals of the calorimeter mechanical support is to avoid the classic
barrel-endcap transition that has plagued most calorimeters at colliders. The basic unit cell
is a “truncated pyramid” geometry (Fig. 2) which can be exactly stacked around the barrel
in azimuth, and stagger-stacked axially. This has been done in the geometry of GEANT4
as shown in Fig. 27 but, of course, without even conceptual supports. The geometry
Figure 27: Drawing of calorimeter from GEANT4 and basic dimensions used in the structural analysis.

of a readout module allows us to contemplate a full calorimeter without a complicated transition with dead regions.

4.3.9 EMI, beam losses, and ‘flyer’ vulnerability

These optical calorimeters are explicitly immune to EMI, and the electronics at the rear will be (we think) immune to EMI being behind 10 $\lambda_f$ of metal, and only digital signals will leave the ends of the calorimeter.

We expect to read out the Čerenkov fibers in time, just like the scintillating fibers for neutron measurement, as a continuous EM energy monitor of the calorimeter volume. Beam losses and flyers would show up in this Čerenkov volume time history as out-of-time clusters of energy coming from outside the interaction point.

Beam losses, and EMI, will be far more troublesome for the electronics-sensitive pixel vertex and tracking chambers.

It seems that we might need “spoilers”, both material and magnetic, upstream of the IR to stifle both the beam losses and the flyers.
Figure 28: The outer solenoid is supported by a frame, and the inner solenoid is supported by radial spokes for the outer solenoid.

5 Summary of Requests

These three requests are coordinated and are designed to lead to a calorimeter EDR by 2010. In addition, this stand-alone EDR will be integrated with other concepts on an ad hoc trial basis. We have reached a level of detail and understanding that in the 4th Concept group that we are able to address more complex issues.

The fund requests have been split between the two main US institutions, ISU and
Figure 29: The vertical displacements and distortions of the solenoids.

TTU, and these funds would be dispersed to the working groups by standard University mechanisms for the transfer of research funds.
Figure 30: Axial stresses on the inner solenoid. We have some design work yet to do on the solenoids, and have already moved the wall of coils out to relieve these stresses, which go like $1/z^3$.

References

[1] The first mention of this dual-readout as a means to improve hadronic energy resolution was made by Paul Mockett, "A Review of the Physics and Technology of High-Energy Calorimeter Devices", proceedings of the 11th SLAC Summer Institute on Particle Physics, July 1983, SLAC Report No. 267. An unreported, but earlier,
Figure 31: The low frequency vibrational modes of this dual solenoid, radial spokes structure.

Figure 32: The end rings for the barrel (a) and the end cap (b) scalable modules; the support frames for the barrel (c) and the end cap (d).

[2] The first paper on a fiber Cerenkov-scintillation dual readout calorimeter was by Wigmans, discussed in detail in, "Quartz Fibers and the Prospects for Hadron Calorimetry at the 1% Resolution Level", Proceeding for the 7th International Conference on Calorimetry in High Energy Physics, Tucson, 1997. This paper essentially was
the intellectual design of the present DREAM module. The proposal for DREAM was "Dual-Readout Calorimetry for High-Quality Energy Measurements", October 2001, proposal to Advanced Detector Research program of DoE, R. Wigmans, et al. The website containing the proposal, all papers and figures is http://www.phys.ttu.edu/
dream, which can be linked from http://highenergy.phys.ttu.edu.


[16] INFN at Trieste (A. Penzo) and Udine (G. Pauletta).

