Supplemental Proposal to the ALCPG & LCDRD Groups for the Comprehensive Study, Construction and Testing of Multiple Readout Calorimeters of the 4th Concept

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Abstract

We propose a comprehensive assault on the main problems of high-precision hadronic calorimetry for physics at the International Linear Collider (ILC), including *(i)* the design, construction and testing of a cubic-meter dual-fiber readout module to suppress the leakage fluctuations that limited the performance of the 1-tonne DREAM module[1]; *(ii)* measurement of the MeV-neutron content of hadronic showers to suppress binding energy fluctuations in hadronic shower development; *(iii)* further testing of a dual-readout crystal front-end to the fiber calorimeter to achieve better $e^{\pm}$ and γ measurements; *(iv)* design of a photoconverter to replace the PMTs used in the DREAM beam tests, *(v)* additions to the GEANT 4 package to improve the simulation of the main features of hadronic calorimetry, in particular, the known and well-measured EM fraction compensation mechanisms, neutron compensation mechanisms, electromagnetic content measurements, and the differences between pion and proton showers in highly non-compensating calorimeters; and, *(vi)* a slice test of the 4th concept design with a muon system behind the cubic-meter module and a TPC prototype in front. The goal is a complete test of the calorimeter principles and a demonstration of the particle identification probabilities and the spatial and energy a resolution capabilities of a "full" 4th concept detector.

This proposal directly addresses the highest priority issue of the 4th concept: the energy and spatial resolutions of hadronic showers in a dual-readout calorimeter with a geometry that can be scaled to a full ILC detector and with a TPC in a magnetic field.

This work follows directly from our previous beam tests of the small 1-tonne prototype DREAM module. In a series of papers describing a wide variety of dual-readout calorimetric measurements of hadrons and jets [1], electrons [3], muons [4], the different spatial distributions of Čerenkov and scintillation light in showers [5], and the separability of Čerenkov and scintillation light in a single optical medium [6], we have shown, in this small module calibrated with 40 GeV electrons, that the electromagnetic response is linear from 20 to 200 GeV, hadronic response is linear from 30 to 300 GeV, the energy response is Gaussian, and the energy resolution is improved over the case of a pure scintillating calorimeter.

The main goal, or milestone, is a module that is sufficiently massive that leakage fluctuations are not a concern for energy resolution, and a module that achieves an energy resolution of

$$\frac{\sigma_E}{E} \approx \frac{20\%}{\sqrt{E}},$$

or better, for incident pions or interaction jets. This test cannot be made with less funding and this goal represents a critical and central milestone for the 4th concept.

No other concept group is working on dual and multiple readout calorimetry, and we welcome both participants and observers. This proposal, in essence, was submitted to the Damerell committee [2] some months ago, and the calorimeter module costs remain unchanged. Since this is our only need, it is proposed here with the additions of software and simulation work, dedicated electronics, and the extra costs of a slice test.

[1] The DREAM module was never intended to achieve high-precision and was limited to 1-tonne of Cu by funding constraints, but it did achieve its goal of demonstrating that a dual readout calorimeter is easily feasible and offers several substantial benefits for experimental calorimetry.

[2] This was an informal request to the concept groups for their critical R&D needs.

Collaborators are all 4th Concept participants and other interested members of the ILC detector community, especially TPC and pixel vertex detector proponents, for a "slice test" of multiple and sequential ILC detectors in a beam.

The dual-readout calorimetry The main idea of multiple readout calorimetry is to independently measure those physical quantities that fluctuate in a hadronic shower and that lead to fluctuations in energy response, and sum over those physical quantities that do not lead to fluctuations in energy response. Thus, the huge fluctuations in electromagnetic energy fraction, f_{em}, are directly measured with Čerenkov light generated in clear plastic fibers primarily by the very relativistic electrons in the shower, the transverse spatial fluctuations are sampled on the millimeter scale with high spatial density optical fibers, the fluctuations in binding energy losses will be measured by the MeV neutrons in the volume, whereas the longitudinal depth development fluctuations are summed in depth. This last statement may, at first, seem counter-intuitive, but it is a great strength: hadronic showers with widely differing depth deposition fluctuations have the same total light output independent of their depth development [9].

The calorimetric measurement of hadronic particle energies has been bedeviled for decades by

1. poor energy resolution, typically $80-120\%/\sqrt{E}$ for big detectors. There are a few exceptions, such as ZEUS at DESY, with $e/h \approx 1$, which consequently fixed the senser-absorber ratio at a low value;

2. non-Gaussian response. Usually, a high-side tail[3] is a characteristic of hadron calorimeters;

3. non-linearity with energy. The calorimeter response is not linear with incident particle energy.

These serious deficiencies are generally understood to be due to several factors: a non-equal response to electromagnetic and hadronic shower energy deposits ("$e/h \neq 1$"), the fall-off of calorimeter response to lower energy hadrons in the few-GeV region, the huge fluctuations in electromagnetic energy fraction from shower-to-shower, the degrees of absorption of neutrons, the integration time of the signal especially in regard to the slower neutron signal, and variation of the mean electromagnetic shower fraction with increasing hadron energy. These phenomena affect the above list of problems in different ways. This dual-readout calorimeter has the following main features, as can be seen in the paper on hadronic energy measurement [1]:

1. the energy resolution is expected to be excellent, about $20-25\%/\sqrt{E}$ for π's and "jets" in a module with negligible leakage fluctuations;

2. the response is Gaussian, to a good approximation; and,

3. the response is linear in hadronic beam energy in a *calorimeter that was calibrated only with 40 GeV electrons.*

[3]It is clear that a high-side calorimeter energy tail can generate fake high-mass objects and must be avoided.

Of these three beneficial features, the third is probably the most important. At the ILC, a detector will be calibrated at the Z^0, *i.e.,* 45 GeV $e^{\pm}$, $\mu^{\pm}$ and *jets*, and will be expected to measure with high precision the energies of particles and jets up to 500 GeV. This factor of 10 extrapolation will require a lot of faith, because there will be no test beam.[4] However, in the 4th concept detector, this capablility is intrinsic to the calorimeter itself. The device is explicitly linear on the mm spatial scale, and the direct simultaneous measurements of electromagnetic and hadronic energies are coupled so that a calibration with electrons results in linear hadronic energy response.

Dual readout crystal front section The DREAM module was exposed to an electron beam from 20 to 200 GeV and, since the scintillating and Čerenkov fibers are both equally sensitive to electromagnetic showers, the response functions are essentially the same. However, the Čerenkov resolution is limited by the finite photoelectron (*pe*) statistics of $\sim 18pe/\mathrm{GeV}$, whereas the scintillation luminosity was a factor of 20 higher, but still limited to $20.5\%/\sqrt{E} + 1.5\%$. We have begun the testing of $PbWO_4$ crystals for dual-readout of scintillation and Čerenkov light [10] to achieve greatly enhanced *pe* yield and therefore better EM energy resolution. The smaller channel size will yield better spatial resolution on electrons and photons. The dual-readout will allow these advantages without losing hadronic energy resolution.[5] Preliminary results from our LCRD proposal [7] were presented at the Elba conference [10] and parts were presented at CALOR06 [11].

Proposed work We propose to test additions and improvements over the present tested proof-of-principle DREAM module, *viz.*,

1. a dual-readout crystal front section with excellent transverse segmentation and excellent electromagnetic energy and spatial resolutions;

2. each fiber will be inserted into its own groove; this will increase the statistical resolution over the DREAM module by reducing the correlation in multiple fiber signals (both scintillating and Čerenkov) arising from the passage of a single track;

3. construct the absorber matrix of brass.

4. readout both the scintillating fibers and the Čerenkov fibers in time, out to about 300 ns, to catch the slow neutrons whose energy is roughly proportional to the binding energy (BE) losses in nuclei in hadronic showers. These neutrons are approximately $T \sim 1$ MeV, and their velocity is $v \approx \sqrt{2T/M_n} \approx 0.05c$. For a mean neutron interaction length of several centimeters, the expanding neutron

[4] All calorimeters in most experiments at high energies have this problem, and specifically the HF calorimeters on CMS must measure 3 TeV jets having been calibrated only on 0.3 TeV pions. There is a scheme to pitch the 7 TeV proton beam with a bent crystal into HF to calibrate. This would be harder to do at the ILC. A good problem to solve would be the design of a halo proton scraper during LHC running to achieve a parasitic low flux TeV-scale beam.

[5] Roughly, half of all hadrons interaction in the "EM" section, which must therefore also be a "hadronic" section.

content produced by a showering jet will fill possibly 0.5 m^3 over a few hundred ns;

5. use a photoconverter with both higher quantum efficiency, a smaller photosensitive surface to reduce the probability of a direct hit of a particle on the sensitive area of the photoconverter, and that is not sensitive to a magnetic field. This could be the new MultiPhoton Counter (MPC) or another variation of the Silicon Photomultiplier[7]; and,

6. develop the photoconverter to plug directly onto the fibers as they exit the rear of the calorimeter mass to achieve zero stray fiber length, and a minimum of readout space. Integrate the fibers, photoconverters, FADCS and electronics on one board.

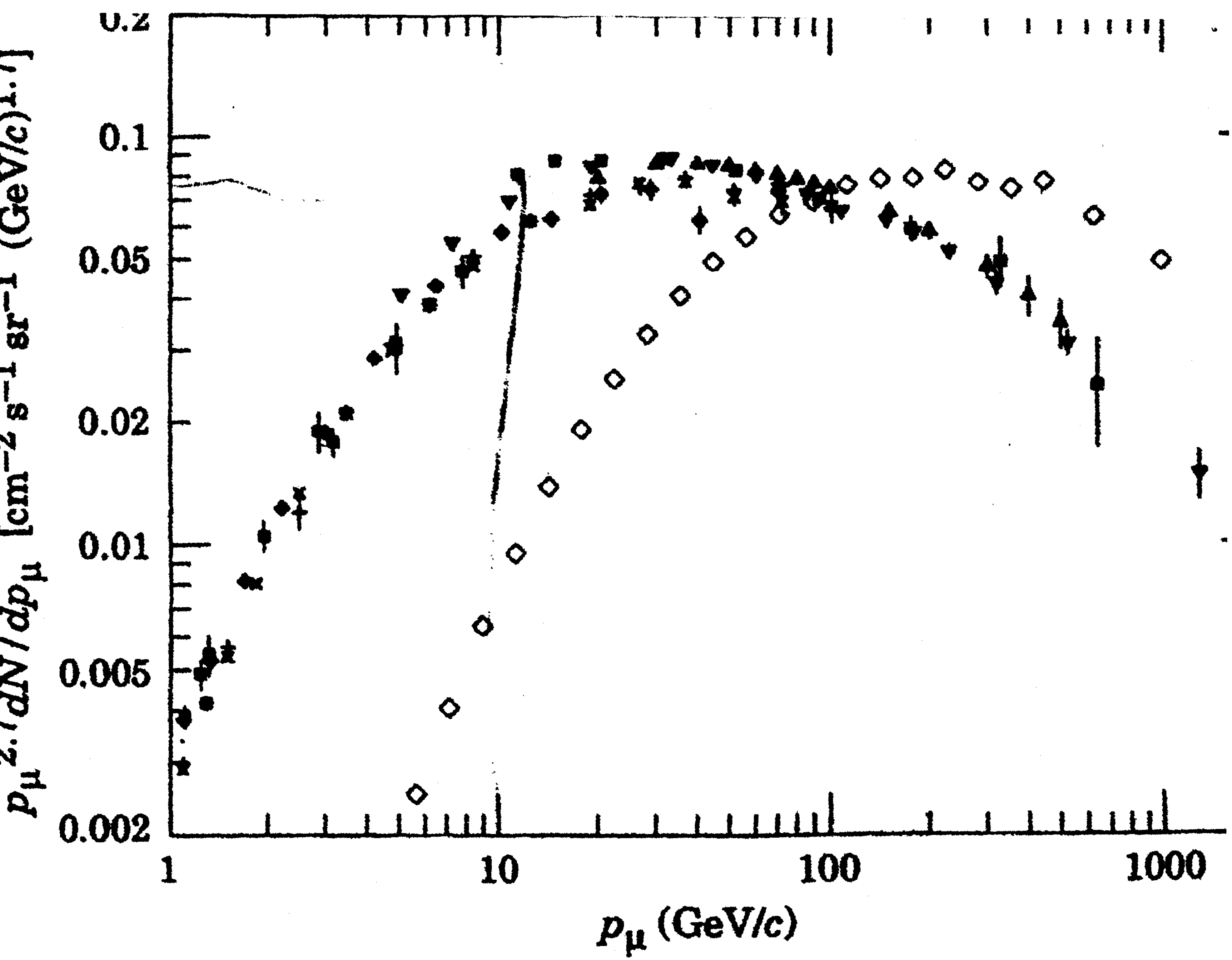
These multiple-fiber hex geometry calorimeter modules with light readout at the back are perfectly suited for a zero-crack and zero-dead volume calorimeter. Fibers can be in grooves at 1mm from the edge of a module, and therefore be positioned without dead space to an adjacent module. The volume fiber density can be kept constant across the boundaries between modules.

Triple Readout (measuring the neutrons) The success and the simplicity of the dual readout calorimeter has led us to ask the obvious question: What is the next largest fluctuation in a hadronic shower, after the electromagnetic fraction fluctuation, and how can we measure it [8]. The correlation between the kinetic energy of the neutrons produced in a 100 GeV π^- hadronic shower in DREAM , and the $np \to np$ signal seen in the scintillating fibers is shown if Fig. 16 of the DOD [13], and although this correlation is not exact, it is good enough that we claim to measure the binding energy losses by measuring the MeV neutrons.

This fluctuation is the binding energy losses in nuclear break-up and is proportional to the number of 1-2 MeV neutrons in the calorimeter medium. Neutrons in this energy range are most easily measured by presenting them with a hydrogenous medium, usually a hydrocarbon, and then measuring the proton elastic recoils from the $np \to np$ scatters. The kinematics of equal-mass elastic scattering are that the neutron loses on average one-half of its kinetic energy per collision, *i.e.,* the proton recoils are in the MeV range and are easily detected in, for example, a plastic scintillator. This is the most obvious technique for measuring the neutrons. Of the four methods listed in the 4th Concept DOD, we will test two:

1. **Time history of S and C fibers**

   MeV neutrons are slow, $v_n \sim \sqrt{2T/M_n} \sim 0.05$c, so $np \to np$ scatters will show up later in the scintillation fibers, illusrated in Fig. 17 of the DOD [13], and spread out over a larger volume. We can use the Analog Transient Waveform Digitizer (ATWD)[15] to achieve time buckets of 1-2 ns lasting for 300 ns. We would also read out the Čerenkov fibers for three reasons: late $e^{\pm}$ light that might be confused with $np \to np$ can be tagged by simultaneous light in the Čerenkov fibers; we have found in DREAM data that the scintillation lineshape in electron data is time-dependent[6]; and, furthermore, the neutron capture reactions $nA \to A^* \to$ multi$-\gamma$s will be somewhat efficient at yielding $e^{\pm}$ above Čerenkov threshold and therefore be part


0.2
0.1
0.05
0.02
0.01
0.005
0.002
$p_\mu^{2.7} dN/dp_\mu$ [cm^{-2}s^{-1}sr^{-1} (GeV/c)$^{1.7}$]
1
10
100
1000
p_μ (GeV/c)

Budget The following table represents our experience with the DREAM module and two beam tests at CERN.

Component	Description	Institutions	Basis	Cost
Materials and labor	brass absorber S fibers C fibers photoconverters assembly	ISU, TTU, Fermilab	DREAM " " " "	\$ 150K \$ 90K \$ 47K \$ 93K \$ 20K
Engineering	Mechanical: mass fixtures Electronics: design FADC, readout, DAQ	TTU, Fermilab		\$ 10K \$ 20K \$ 20K
Photoconverters	Development	Pavia	non-US funds	-
Crystal dual readout	Development	TTU	existing test	\$ 50K
Electronics	Design, build	TTU, Wuhan, Fermilab	 non-US funds	\$ 10K -
Postdocs	One for mechanical, one for electronics	ISU TTU	\$70K	\$ 140K
Software, simulation	Develop	ISU, IFIN-HH, INFN Lecce		\$ 20K
Miscellaneous	Shipping, travel, student support			\$ 30K
Total, 2 years				\$700K

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