Exploring Crystal Calorimetry for A Linear Collider Detector

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1 Introduction

While there is a strong effort focusing on very compact sampling calorimetry for the future Linear Collider (LC) detector, we propose to explore crystal calorimetry with two kinds of heavy scintillating crystals, lead tungstate ($PbWO_4$) and LSO/GSO, for an electromagnetic calorimeter at the future linear collider.

Historically, total absorption crystal calorimetry has been a choice of precision electron and photon measurements, and needs to be explored as an option for the electromagnetic calorimeter at the LC. Crystals usually have fast signal response to incident particles. They offer good electromagnetic energy resolution, which can be parametrized as $\frac{\sigma_E}{E} = \frac{a\%}{\sqrt{E}} \oplus b\% \oplus \frac{c}{E}$ with E in GeV, where a is typically 1 or 2, b can be controlled to 0.5 to 0.6%, and c is 1 to 100 MeV, depending on the readout noise and crystal light yield. Crystal calorimeters made of heavy crystals with short radiation length and Moliere radius can be compact. They also offer good position resolution with appropriate lateral segmentation.

2 Crystal Investigation

Table 1 shows the choice of the crystals hitherto considered and their relevant properties, namely, radiation length (X_0), response time, Moliere radius, radiation hardness, density, cost, refractive index, and decay time.

Table 1: Useful Characteristics of Some Crystals as Calorimeter Material.

Properties	CsI(TI)	CsI	BGO	$PbWO_4$:Y	GSO:Ce	LSO:Ce
X_0(cm)	1.86	1.86	1.12	0.89	1.39	1.14
R_{Moliere}(cm)	3.8	3.8	2.3	2.2	2.4	2.3
Rad hard(Mrad)	0.01	0.01-0.1	0.1 - 1	100	100	100
Density(g/cm^3)	4.51	4.51	7.13	8.28	6.70	7.40
Cost($/cc)	3.2	4	4	2.5	see text	see text
Refractive index	1.79	1.95	2.15	2.20	1.85	1.82
Decay time(ns)	680	16	300	5	56	47
(slow component)	3340			15	600	

The reason for our choices are clear from the table. Initial tests will be performed with one or two crystals in the lab bench test, using various read-out devices, e.g., Avalanche Photo-diodes (APD), large-area photo-diodes, PMT's, and, vacuum photo-triodes(VPT). The PMT's will be used only in the bench test, since they will not work in high magnetic fields. The APD's are ideal for this and for radiation hardness. The bench test will measure number of photo-electrons detected per MeV, and corresponding photon/MeV yield for the crystal. We will also investigate the uniformity of the crystals.

2.1 $PbWO_4$

The Yttrium doped lead tungstate crystals, used by the CMS experiment at LHC, are mass produced by Bogoroditsk Techno-Chemical Plant in Russia and Shanghai Institute of Ceramics (SIC) in China. They are available at low cost, typically 2.5 to 3 $/cc in large quantity. It, however, has low light yield as shown in Table 1. Using different dopants, SIC has increased the photon yield tenfold mainly in the μs decay component without altering other properties. In addition, these $PbWO_4$ crystals still have a fast component with $\sim$ 10 ns decay time.

We will investigate the light yield of both Yttrium doped $PbWO_4$ crystals and the $PbWO_4$ crystals with high light yield from SIC. Evaluation will also be made to see if the fast component provides sufficient photons, e.g. for energy measurement or for triggering, and if the signal over the background is sufficient for the LC physics by using either the fast component or the sum of the two components. The light yield for both the fast and the slow components will be measured with various readout devices. The light yield and response uniformities and the linearity will also be measured to see if they are in the accessible range. Photo-electron collection at both the near and the far face will also be measured to study the propagation of the signal in the crystal. In a longer term we would test the response of the crystals with a beam, where the linearity of response over a large range can really be tested. It would be desirable to acquire a 5×5 crystal matrix for the beam test.

We will use Yttrium doped lead tungstate of the kind used by CMS, and the two kinds of high-photon-yield types produced by SIC. The latter is not yet available commercially, but may be obtained by one of us, Ren-Yuan Zhu, who has an R&D contract with the SIC. He expects to obtain high quality Yttrium doped $PbWO_4$ samples about three months after the order is placed. We plan to procure two crystals (of each type) of $\sim 1.2 - 1.3$ Moliere radii square surface and ~ 25 radiation lengths depth.

2.2 LSO:Ce/GSO:Ce

Cerium doped LSO and GSO are also potentially very desirable crystals. They are mainly used in small size in medical applications, so are expensive commercially. The expected cost for large size LSO is $50/cc. The LSO:Ce is produced only by CTI, a company that produces PET scattering by using LSO:Ce and BGO, while the GSO:Ce is produced by Hitachi. As seen from Table 1, both LSO:Ce and GSO:Ce have very high light yield, short radiation length and small Moliere radius etc. The cost of LSO:Ce and GSO:Ce, however, may be significantly reduced if they are mass produced for high energy and nuclear physics applications. Historically, initial high crystal costs at the R&D stage were substantially reduced as improvements were made in production in large quantities. It is not unlikely that in the future, the cost of production for these crystals will also decrease substantially. As with $PbWO_4$, similar bench tests need to be performed; uniformity study and signal propagation studies are very important.

3 Simulation

Another aspect of our R & D plan is to simulate the crystal response properly based on the bench test data. The bench tests performed in the lab will provide adequate information to crudely model the crystal behavior. The beam test, however, will provide the final and more accurate details. With the data from the bench test, we will study various types of segmentation for the full calorimeter with a full detector Monte Carlo. Some discussions have already been initiated with the simulation group at SLAC.

The beam test will allow us to verify the simulation of the crystal behavior in detail. Once this is achieved, we can then test various segmentation schemes, especially longitudinally, to allow for energy flow measurements. Hence, various calorimeter parameters need to be optimized in the full detector Monte Carlo and necessary resolution for various physics processes checked. This is a critical part of the study to determine the final choice for the calorimeter. The Energy flow concept to improve jet measurements is an important aspect of calorimetry at the LC. We are interested in two issues concerning the application of the energy flow: one is the physics limitations to the jet resolution and the other is whether longitudinal segmentation would help in improving jet resolution. Zhu is particularly interested in studying the effects of jet resolution from perturbative QCD as well as from fragmentation.

4 Deliverables and Resources

The goal for the first year is to test the light yield for the three types of $PbWO_4$ crystals with various readout schemes (mainly PMT's initially), including fast and slow responses of the two high-photon-yield types. Also measure signal propagation through the crystal by observing the difference in responses with readout attached to the front and then in the back side of the crystals. Next we would like to test the uniformity of response, along with the energy division between two adjacent crystals.

Most of the proponents are collaborators in BABAR, and therefore maintain close contact. Jack Ritchie is presently involved in the BABAR (CsI) calorimeter, the construction of which was led by Rafe Schindler and Bill Wisniewski. Schindler will provide lab space and any incidental technician help when needed. Usha Mallik, Milind Purohit and Sridhara Dasu from

Wisconsin will provide a graduate student each to carry out these tests with regular supervision by Mallik. Dasu is committed to CMS in addition to BABAR, and therefore will not participate in the proposal. Zhu will provide his expertise along with procuring the crystals. Local supervision will be provided by Schindler, and to some extent by Bill Wisniewski from SLAC. Because of his new role as the technical coordinator of BABAR, he will be available in an advisory role only.

5 Long Term Goal

This program in FY03, hopefully, is the beginning of a long term project aiming at building a crystal calorimeter for the linear collider. As mentioned earlier, the next step to the FY03 program is to test the crystals in a beam with a crystal matrix, with and without longitudinal segmentation. The beam test results with a prototype crystal matrix together with the Physics and detector simulations will help to establish the feasibility of an electromagnetic crystal calorimeter at the linear collider.

6 FY03 Budget

A total of $49,000 is requested to cover the FY03 cost (no indirect cost included). Table 2 lists the break down of the budget. Two of each kind of $PbWO_4$ crystals are to be procured. Because of the high cost, we will try only one crystal of LSO:Ce or GSO:Ce with the volume of $\sim$ 250cc.

Table 2: Budget for the First Year R&D.

item	quantity	cost in $
$PbWO_4$	six crystals	5,000
LSO:ce or GSO:Ce	one crystal	15,000
Readout Electronics	APD, PMT etc	10,000
Travel	To Caltech and back	3,000
0.5 supplement	two students	16,000
Total	One year R&D	49,000

To read out the lead tungstate with sources we need high gain PMTs, hence two Hamamatsu R2259 will be used in addition to two APD's, 2cm×2cm photo-diodes, and VPT's. Along with the associated electronics we estimate $10,000 for all readout components. For the two students from South Carolina and Iowa, a supplemental equivalent for each student to be resident at SLAC is added. A small amount of $3,000 for travel between Caltech and SLAC (or Iowa or South Carolina) is added.
One of us, Jack Ritchie, is not asking for any funds in the first year; also, it is possible that other faculty members from UT Austin may join this R&D effort in the future. Rafe Schindler and any other participation from SLAC in this R&D will be funded by the lab.