A Study on Dual Readout Crystal Calorimeter for Hadron and Jet Energy Measurement at a future Lepton Collider

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Studies of requirements and specifications of crystals are necessary to develop a new generation of crystals for dual readout crystal hadron or total absorption calorimeter. This is a short and basic study of the characteristics and hadron energy measurement of PbWO₄ and BGO crystals for scintillation and Cerenkov Dual Readout hadron calorimeter.

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I. INTRODUCTION

Scintillation and Cerenkov Dual Readout Calorimeters are excellent candidates for the calorimeters to have the high precision of $30\%/\sqrt{E}$ for hadron jet energy measurement required for the future large lepton colliders Muon Collider, CLIC, ILC [1–6]. L3[7] used BGO, and CMS[8] is using PbWO₄ for their EM calorimeters. Scintillation and Cerenkov Dual Readout using BGO, PbWO₄, and various crystals as EM calorimeter in combination with the Dual Readout fiber Hadron Calorimeter have been studied extensively with test beam data and simulation studies [1, 2, 4]. Feasibility studies are being performed for the proposed Total Absorption Crystal Calorimeter[9, 10] to use crystal[11] for both the EM calorimeter and the Hadron calorimeter for measuring hadron and jet energy.

The main questions on Dual Readout Crystal Total Absorption or Hadron calorimeter are:

- Requirements and Specifications[12, 13] for producing affordable crystals
BGO cost[12, 13] is \$10 per cm³. The cost for a 100 m³ BGO calorimeter would be a prohibitive \$1 billion. As Alexander Gektin summarized on Oct. 27, 2009 in the Fermilab Research Techniques Seminar,[12] criteria and specifications are necessary to develop a new generation of crystals for Total Absorption Crystal calorimeter. PbWO₄[8] with a cost of \$3 per cm³ is more affordable than BGO. The cost of crystal for dual readout hadron calorimeter should be $\approx$ \$1 per cm³.
- Interaction lengths and Leakage
Studies based on data from 1980s experiments have shown that 8 interaction lengths, needed to contain 95% of 300 GeV pions, are required for CLIC[14] and/or Muon Collider[3] calorimeters. CsI and other lower density crystals would not have the required interaction lengths. For the same detector geometry and size, PbWO₄ would have more interaction lengths for more containment of hadron showers than BGO. With the CCAL02 geometry in the present simulation, the EM + HA Crystal Calorimeter BGO has 5.8 interaction lengths while PbWO₄ has 7 interaction lengths. Alternatively, for the same number of interaction lengths, crystals such as PbWO₄ with higher density than BGO, would enable having smaller radius for the calorimeter and the solenoid.
- Crystal characteristics
The light yields, which may be an important consideration for energy measurement, are relatively $\approx 50 : 1$ for BGO and PbWO₄. The signal decay time is 300 ns for BGO and 30 ns for PbWO₄. The crystal to be developed for dual readout hadron calorimeter must enable excellent measurement of Cerenkov and scintillation signals.
- Segmentation and Calibration
The calorimeter segmentation and necessary calibration will be a major issue and will need extensive study, which will require digitization and simulation of the photon detection efficiency and calibration of scintillation and Cerenkov optical readout, for example, with the Silicon Photomultiplier, SiPM.
- Detector simulation Physics Models
Geant4 and FLUKA simulation software are commonly used. The models/parameters QGSC, QGSP, QGSP_BERT, LHEP, LCPHYS in GEANT4 simulate different detector responses. BGO calorimeter response for the above physics models have been reported by Hans Wenzel at ALCPG09 Workshop [6]. Test Beam data

is needed for Validation of Simulations. A study using charged tracks, to correct for the effects of the magnetific field for Jet and Jet-Jet mass reconstruction, has also been reported by Adam Para at ALCPG09 Workshop.[6]

Feasibility studies of dual readout crystal calorimeter will require simulation studies similar to this study, with crystals of various characteristics, to develop new types of crystals. In this short study, we compare the hadron energy measurement for BGO and PbWO4 dual readout crystal calorimeter, for 2 sizes of segmentation.

Simulation is briefly described in Section II. Analysis is outlined in Section III. Results are shown in Section IV. The Summary is in Section V.

Additional plots are also provided in Appendix A. Some of Hans Wenzel’s results [5] from helping this study are in Appendix B. Introductory Computing info are listed in Appendix C. Dual Readout Crystal Calorimeter analysis framework is given in Appendix D, The necessary modifications from BGO Simulation to PbWO4 Simulation are listed in Appendix E. Information and example for using Open Science Grid (OSG) are listed in Appendix F.

II. SIMULATION

The two main types of particles simulated are:

- Single particles, electrons, pions at various energies (Table I) to provide C/S calibration, energy containment, and energy resolution studies.
- Single W and single Z , with momentum 50, 100, 200 GeV/c, for studying di-jet mass resolution.

Single particles:								
Energy (GeV):	π^-	1	5	10	20	50	100	200
	e^-			10		50		

TABLE I: Pion and e^- Single particle Energies

The main Calorimetry characteristics are: Response, Linearity, Containment, Shower shape, and Energy Resolution. The dual readout crystal calorimeter feasibility studies must have comparisons of various crystals. Because of this study, PbWO4 Crystal detector type was created

`/ilc/ild/wenzel/ccal02/ccal02_PbWO4` and `/ilc/ild/gpyeh/ccal02/ccal02_PbWO4`

To study Interaction Lengths and Energy Leakage, we also created “PbWO4_d15” (with density = 15) Crystal detector

`/ilc/ild/gpyeh/ccal02/ccal02_PbWO4_d15`

Also because of this study, Adam Para and Hans Wenzel wrote a script to enable creating crystal detectors with different density and/or different transverse segmentation. We study π^- energy resolution for BGO and PbWO4 Crystals, and for density = 10, 15, 20 g/cm³.

In the CCAL02 simulation, the detector segmentation (Table II) has been:

	Layers	length/layer cm	depth cm	Segmentation cm x cm	inner radius cm	outer radius cm	inner z max cm
Ecal Barrel	8	3	24	3 x 3	127	151	192
Hcal Barrel	17	6	102	5 x 5	151	253	294
Total Barrel	25		126				
Ecal Endcap	8	3	24	3 x 3			
Hcal Endcap	17	6	102	5 x 5			
Total Endcap	25		126				

TABLE II: Crystal Calorimetry Segmentation. BGO and PbWO4 crystals have 5.8 and 7 Interaction lengths, respectively. We use 1.5x1.5x3 for the second Ecal segmentation size, and 2.5x2.5x6 for the second Hcal segmentation size.

In the detector description/geometry: Barrel EM calorimeter radius = 24 (127 to 151) cm within $z = \pm 192$ cm; HAD calorimeter radius = 102 (151 to 253) cm, within $z = \pm 294$ cm; Solenoid (5 Tesla) starts at 255 cm radius, within $z = \pm 288$ cm. The CCAL02 crystal calorimeter simulation has no gaps longitudinally between crystals.

The L3 BGO [7] and CMS PbWO4 [8] Electromagnetic calorimeters both have truncated-pyramid-shaped crystals arranged in the projective geometry, minimizing transverse and longitudinal gaps in the calorimeter. In the future, more realistic geometry of the CCAL02 calorimeter, including shapes and gaps, should be implemented for the Crystal Calorimeter simulation studies.

Studying the longitudinal segmentation will be important. Varying longitudinal segmentation is not yet implemented in the CCAL02 simulation. In the future, the simulation should have:

Light Yields (maybe this is already correct ?)
 photon detection efficiencies,
 more realistic geometry (including support for 700 tons of crystal ?)

These can take quite some time to implement. Segmentation studies would be more meaningful when we have the above. Mark Fischler mentioned also the effect of the angle of the light. Calibration is an important issue for calorimetry. Experimentalists know that these take lots of work and time. Just getting the correct "dual readout correction" (Over-correction? Energy dependence ? as indicated in Appendix B) seems challenging and may need quite some time.

For the Crystal Dual Readout calorimeter CCAL02 simulation studies including this one, the Simulation tools (Appendix C, D, E, F) are: SLIC simulation environment, GEANT4 LCPHYS physics list, Optical calorimeter by Hans Wenzel, lcsim.org jas3 analysis framework. The simulation, computing, and analysis resources are available on ilcsim.fnal.gov and ilcsim2.fnal.gov clusters. Larger samples are produced on FermiGrid and Open Science Grid (OSG).

III. ANALYSIS

Each high energy hadron interaction produces secondary particles. On average, about 1/3 of the secondary particles are neutral pions which quickly decay into 2 photons producing subsequent electromagnetic showers. The other hadronic secondary particles are mostly charged pions and deposit energy in the calorimeter through dE/dx ionization or interacts hadronically and create subsequent showers. The ratio of neutral to charged, the em fraction f_{em} , increases with hadron energy, and causes non-linear hadronic energy response of calorimeters. The large fluctuation in f_{em} , dominantly causes the poor energy resolution from the traditional calorimetry based on scintillation signal alone. A calorimeter with Cerenkov (C) and Scintillation (S) dual readout enables the direct measurement of both the electromagnetic neutral component and the charged component for each hadron shower, thus provide significantly improvement in the precision of the hadron or jet energy measurement.

The 2nd largest fluctuation fluctuation is the missing energy due to nuclear breakup. Measuring also the slow neutrons from the hadron shower could further improve the hadron energy measurement.

The calibration of the calorimeter scintillation and Cerenkov response to be achieved with electrons and pions with the same energy, to measure the e/h ratio, which is an important characteristic of each calorimeter, calibrating $\left(\frac{e}{h}\right)_C$ and $\left(\frac{e}{h}\right)_S$. For each hadron, the C/S ratio provides a measurement of f_{em} . For hadrons with the same energy, the scintillation response relates linearly with f_{em} . Energy measurement is improved by correcting the scintillation response with C/S and e/h.

For the crystal density and hadron shower leakage study, the first and most important measurement is the raw Scintillation energy deposition, for incident charged pions at different energies (e.g. 10, 20, 50, 100 GeV), for crystals of different densities or with different interaction lengths.

Calibration for the crystal calorimeter is being done by establish calibration factors for C and S signals using 10 GeV electrons, and calibrating the response of hadrons using 10 GeV pions. The scintillation energy deposition for 10 GeV e^- for BGO and PbWO4 is shown in Figure 1. Calibration should probably be done using 50 GeV electrons, and calibrate response of hadrons using 50 GeV pions. The $Z \rightarrow e^+e^-$ events would be the events for calibration in a real detector, and are excellent for the Monte Carlo simulations. Examples of Cerenkov and scintillation response for 10 GeV and 50 GeV e^- are shown in Figure 17.

FIG. 1: LCPhys BGO and PbWO4 scintillation energy deposition for 10 GeV e^-

Dual Readout Correction				per GeV
e 10	C	1.083 e-5 / 1.30 e-3		1.30 e-4
e 10	Edep	0.0277 / 9.94		0.994
e 20	C	1.59 e-5 / 2.60 e-3		1.30 e-4
e 20	Edep	0.0465 / 19.9		0.995
e 50	C	3.30 e-5 / 6.51 e-3		1.30 e-4
e 50	Edep	0.125 / 49.8		0.996
e100	C	4.51 e-5 / 1.30 e-2		1.30 e-4
e100	Edep	0.155 / 99.6		0.996

For the crystal density and hadron shower leakage study, the first and most important measurement is the raw Scintillation energy deposition, for incident charged pions at different energies (e.g. 10, 20, 50, 100 GeV), for crystals of different densities or with different interaction lengths.

Energy deposition and dual readout corrected energy in BGO, PbWO₄, d15 are shown for 20 GeV π^- in Figure 2, and for 100 GeV π^- in Figure 3. Compared with the Energy deposition as determined from the scintillation signal alone, the dual readout corrected energy has improved energy resolution, as observed in these Figures and also summarized in Table III. The "d15" crystal with density = 15 g/cm³ has better energy resolution than BGO or PbWO₄, which have fewer interaction lengths due to their lower density.

Cerenkov signal C vs. Scintillation signal S for 100 GeV π^- in BGO, PbWO₄, d15, d20 are shown in Figure 4. The signal leakage is evident for BGO with 5.8 interaction lengths or PbWO₄ with 7 interaction lengths.

Energy deposition S in BGO, PbWO₄, d15, d20 for 200 GeV π^- are shown in Figure 5. The significant energy leakage is observed for BGO with 5.8 interaction lengths or PbWO₄ with 7 interaction lengths.

A. Dual Readout Correction

Cerenkov and Scintillation Dual Readout calorimetry improve the hadron energy resolution, as have been demonstrated by the DREAM and 4th Collaborations, [1, 2, 4, 6] and by the recent CCAL02 studies.[5, 6] The improvement in hadron energy resolution because of Scintillation and Cerenkov Dual Readout is observed in Table III and Figure 6.

The dual readout correction to the scintillation signal depends on the C/S calibration for the characteristics (e.g. Light Yield, density) of the calorimeter, and likely also the geometry including segmentation of the calorimeter. Meaningful study of Dual Readout correction would require more realistic simulation than the present CCAL02.

For the present CCAL02 studies, Adam Para uses QGSP_BERT in GEANT4. The scintillation and Cerenkov signals are calibrated using 10 GeV electrons, with $\text{Mean_S_Edep} = 9.9845$ and $\text{mean_Cheren} = 0.0015304$ and the Dual Readout correction $\text{Scorrected} = S/(0.681 + 0.311 \times C/S)$ is applied to the scintillation signal to improve energy measurement.

Hans Wenzel usually uses LCPhys in GEANT4, with various Dual Readout corrections. Examples of Hans' Dual Readout corrections and results are shown in Appendix B. After looking into comparisons of different crystal densities (BGO, PbWO4, d15) and hadron shower leakage, Hans is considering energy dependent corrections.

For the Muon Collider, the calorimeter should have at least 8 interaction lengths (see Figure 14). The Test Beam dual readout hadron or total absorption crystal calorimeter should have ≥ 10 interaction lengths, large enough to contain $> 95\%$ of 100 GeV charged pions.

FIG. 2: Energy deposition (left) and dual readout corrected energy (right) for 20 GeV π^- in BGO, PbWO4, D15

FIG. 3: Energy deposition (left) and dual readout corrected energy (right) for 100 GeV π^- in BGO, PbWO4, d15

FIG. 4: C vs. S for 100 GeV π^- in BGO, PbWO4, d15, d20

FIG. 5: 200 GeV π^- energy deposition, Edep, in BGO, PbWO₄, d15, d20

IV. RESULTS

A. Interaction Lengths and Leakage

The rms/mean vs E before and after Dual Readout C/S Correction for crystal density = 7.13 BGO, 8.3 PbWO₄, d15. are shown in Table III and in Figure 6.

The fraction of energy observed, Edep(S) / E, and rms/mean of (Energy deposition, Edep (S)), in BGO, PbWO₄, d15, d20 for π^- with 10, 20, 50, 100, or 200 GeV energy are shown in Table IV and Figure 7.

In this brief simulation comparison study, hadron shower leakage is clearly observed in Figures 2, 3, 4, 5, 6, 7 and in Table III and Table IV for BGO with 5.8 interaction lengths and PbWO₄ with 7 λ_I , but not for d15 and d20 crystals with densities of 15 g/cm³ or 20 g/cm³. With 5.8 or 7 interaction lengths, the hadron shower leakage significantly degrades the hadron energy resolution before and/or after dual readout correction.

The hadron shower leakage, as shown in APPENDIX B, has also been observed [5] and confirmed by Hans Wenzel after the start of this short study. Data from previous experiments and studies indicate that 8 interaction lengths to contain 95% of 300 GeV pion.[14]

In addition to this short study with variable crystal density, other ways to study hadron shower containment and leakage could be:

- 1) varying the thickness of the hadron calorimeter in CCAL02 (may also need to change the radius and magnetic field of the solenoid)
- 2) simulation of a Test-Beam-like test detector with variable hadron calorimeter thickness. .

Crystal	Density [g/cm ³]	X ₀ [cm]	λ_I [cm]	N [λ_I]	10 GeV π^- rms / mean	20 GeV π^- rms / mean	50 GeV π^- rms / mean	100 GeV π^- rms / mean	200 GeV π^- rms / mean
LCPhys BGO	7.13	1.12	21.88	5.8	1.1/7.1 1.0/9.9	2.5/15.3 2.2/20.0	6.7/39.0 6.0/49.9	14.4/78.0 13.4/97.9	29.9/155.2 26.1/166.7
LCPhys PbWO4	8.3	0.9	18	7	1.0/7.2 0.9/9.9	2.1/15.5 1.7/20.3	5.5/39.9 4.6/51.2	11.3/80.5 9.6/101.6	23.9/161.4 23.1/199.2
LCPhys d15	15				0.82/7.5 0.70/9.5	1.4/16.2 1.0/19.8	2.7/42.1 1.5/51.0	4.8/85.5 3.6/102.3	

Crystal	Density [g/cm ³]	X ₀ [cm]	λ_I [cm]	N [λ_I]	10 GeV π^- rms / mean	20 GeV π^- rms / mean	50 GeV π^- rms / mean	100 GeV π^- rms / mean	200 GeV π^- rms / mean
rms / mean									
LCPhys BGO	7.13	1.12	21.88	5.8	0.155	0.163	0.172	0.185	0.192
				5.8	0.101	0.110	0.120	0.137	0.157
LCPhys PbWO4	8.3			7	0.139	0.135	0.138	0.140	0.148
				7	0.091	0.084	0.090	0.094	0.116
LCPhys d15	15				0.109	0.086	0.064	0.056	
					0.074	0.051	0.029	0.035	

TABLE III: rms / mean (upper line) and Dual Readout corrected rms / mean (lower line) in BGO, PbWO4, d15 for π^- with 10, 20, 50, 100, or 200 GeV energy. (see also Figure 6)

FIG. 6: rms/mean vs E (left) before and (right) after Dual Readout C/S Correction for crystal density = 7.13 BGO, 8.3 PbWO4, d15. (see also Table III)

Crystal	Density [g/cm ³]	X ₀ [cm]	λ_I [cm]	N [λ_I]	10 GeV π^- rms / Edep	20 GeV π^- rms / Edep	50 GeV π^- rms / Edep	100 GeV π^- rms / Edep	200 GeV π^- rms / Edep
rms / mean									
LCPhys d7.13	7.13	1.12	21.88	5.8	1.09/7.77	2.44/16.3	6.73/41.1	14.1/81.5	29.9/161.5
LCPhys d8.3	8.3			7	0.91/7.95	1.89/16.7	5.25/42.4	11.4/84.5	22.3/169.5
LCPhys d10	10				0.72/8.14	1.44/17.1	3.56/43.7	7.60/87.6	15.6/175.7
LCPhys d15	15				0.63/8.40	1.00/17.6	1.78/45.2	3.35/90.9	6.57/183.0
LCPhys d20	20				0.62/8.52	0.92/17.9	1.57/45.7	2.91/92.0	4.86/185.2
Edep (S) / E									
LCPhys d7.13	7.13	1.12	21.88	5.8	0.78	0.82	0.82	0.82	0.81
LCPhys d8.3	8.3			7	0.80	0.84	0.85	0.85	0.85
LCPhys d10	10				0.81	0.86	0.87	0.88	0.88
LCPhys d15	15				0.84	0.88	0.90	0.91	0.92
LCPhys d20	20				0.85	0.90	0.91	0.92	0.93
rms / mean									
LCPhys d7.13	7.13	1.12	21.88	5.8	0.140	0.150	0.164	0.173	0.185
LCPhys d8.3	8.3			7	0.114	0.113	0.124	0.135	0.132
LCPhys d10	10				0.088	0.084	0.081	0.087	0.089
LCPhys d15	15				0.075	0.057	0.039	0.037	0.036
LCPhys d20	20				0.073	0.052	0.034	0.032	0.026

TABLE IV: rms/mean of (Energy deposition, Edep (S)), and Edep(S) / E, in BGO, PbWO₄, d15, d20 for π^- with 10, 20, 50, 100, or 200 GeV energy. (Figure 7)

FIG. 7: S_{Edep}/E vs E , (left) and rms/mean vs E (right) for crystal density = 7.13, 8.3, 15, 20 for π^- with 10, 20, 50, 100, 200 GeV. (Table IV)

B. LCPhys vs QGSP_BERT

Some results using QGSP_BERT physics list in GEANT4 are shown in Table V. “LCPhys is a GEANT4 physics list written by Dennis Wright for simulation of events in ILC detectors.” as described in <http://silicondetector.org/display/ilc/What+is+LCPhys> Other GEANT4 physics lists are shown in <http://silicondetector.org/display/ilc/What+other+Geant4+physics+lists+does+SLIC+support> Comparing Table V and Table IV, some differences between QGSP_BERT and LCPhys and other parameter lists in GEANT4 are observed. For 10 GeV pion, QGSP_BERT has energy deposition of 8.73 GeV but LCPhys has 7.77 GeV. Test Beam data will be needed to validate the GEANT4 physics lists and simulation.

Crystal	Density [g/cm ³]	X ₀ [cm]	λ_I [cm]	N [λ_I]	10 GeV π^- rms / Edep	20 GeV π^- rms / Edep	50 GeV π^- rms / Edep	100 GeV π^- rms / Edep	200 GeV π^- rms / Edep
QGSP_BERT BGO	7.13			5.8	1.16/8.73	2.53/17.9	6.99/44.4	15.5/86.8	
QGSP_BERT d15	15				0.61/9.1	0.90/18.7	1.58/47.6	2.36/95.2	
Edep (S) / E									
QGSP_BERT BGO	7.13			5.8	0.87	0.89	0.89	0.87	
QGSP_BERT d15	15				0.91	0.94	0.95	0.95	
rms / mean									
QGSP_BERT BGO	7.13			5.8	0.133	0.141	0.157	0.179	
QGSP_BERT d15	15				0.067	0.048	0.033	0.025	

TABLE V: rms/mean of Energy deposition, Edep (Figure 8) in BGO, d15 for π^- with 10, 20, 50, 100 GeV energy, using QGSP_BERT list in GEANT4

FIG. 8: 10, 20, 50 100 GeV π^- energy deposition (Table V) in BGO, with QGSP_BERT

C. Segmentation

An excellent example of PbWO4 crystal calorimeter is the CMS Electromagnetic calorimeter.[8] The density is 8.28 g/cm^3 , radiation length $= 0.89 \text{ cm}$, Moliere radius $= 2.2 \text{ cm}$, Index of refraction $= 2.2$. Peak emission $= 440 \text{ nm}$, 85% of Light emission is within 25nsec, and Light Yield is 100 photons/MeV. About 4.5 photoelectrons are collected per MeV in both the barrel and the endcap. Each Central and/or Barrel crystal is 23 cm long corresponding to $25.8 X_0$ (radiation lengths), with front size $= 2.2 \times 2.2 \text{ cm}^2$ and back size $= 2.6 \times 2.6 \text{ cm}^2$. The total crystal volume is 8.14 m^3 , and the total mass is 67.4 tons. A dual readout PbWO4 crystal hadron or total absorption calorimeter would be *geq* 10 times the size of the CMS PbWO4 EM calorimeter.

The L3 EM calorimeter[7] BGO crystals had front size $= 2 \times 2 \text{ cm}^2$, back size $= 3 \times 3 \text{ cm}^2$, 24 cm length, similar area and length as the CMS EM calorimeter PbWO4 crystals.

Hadron showers are contained transversely within a radius of one interaction length from the trajectory of the hadron. Hadron showers have large longitudinal fluctuations over ≥ 8 interaction lengths, and large fluctuations at the end of the shower. Longitudinal segmentation of the dual readout crystal hadron calorimeter should be studied with more realistic simulation including light yields, photon detection efficiency, and support for the 700 tons of crystals.

Because of this study, Adam Para and Hans Wenzel wrote a script to enable creating crystal detectors with different crystal density and/or different transverse segmentation. The significant effects of crystal density have been presented in this note.

Transverse segmentation is not expected to have significant effects on hadron energy resolution, especially for the present CCAL02 simulation which simulates $\sim 100\%$ photon detection efficiency. Transverse segmentation has some effects on jet mass resolution, which is being studied using $W \rightarrow \text{jets}$ events or $Z \rightarrow \text{jets}$ events. Studies with more realistic simulation and longitudinal segmentation will be much more important.

In this short study, the EM calorimeter crystals are $1.5 \times 1.5 \text{ cm}^2$, $3 \times 3 \text{ cm}^2$, $4.5 \times 4.5 \text{ cm}^2$, HA $2.5 \times 2.5 \text{ cm}^2$, $5 \times 5 \text{ cm}^2$, $7.5 \times 7.5 \text{ cm}^2$. The shape of the crystals should be truncated pyramid.

Crystal	Density [g/cm ³]	X ₀ [cm]	λ_I [cm]	N [λ_I]	10 GeV π^- rms / Edep	20 GeV π^- rms / Edep	50 GeV π^- rms / Edep	100 GeV π^- rms / Edep	200 GeV π^- rms / Edep
LCPhys d7.25.15	7.13	1.12	21.88	5.8	7.8 ± 0.01	2.44/16.3	41.1 ± 0.07	81.3 ± 0.14	
LCPhys d7.50.30	7.13			5.8	$1.09/7.77$		$6.73/41.1$	$14.1/81.5$	
LCPhys d7.75.45	7.13			5.8	$1.09 / 7.77$		$6.68/41.0$	$15.2/81.6$	
LCPhys d15.25.15	15				$0.63/8.40$	$1.01/17.6$	$1.80/45.1$	$3.36/90.9$	
LCPhys d15.50.30	15				7.5 ± 0.01	16.2 ± 0.01	42.1 ± 0.03	85.5 ± 0.05	
LCPhys d15.75.45	15				$0.63/8.40$	$1.00/17.6$	$1.81/45.1$	$3.29/90.9$	
LCPhys d20.25.15	20				8.5 ± 0.01	17.9 ± 0.01	45.7 ± 0.02	92.0 ± 0.03	

TABLE VI: rms/mean of Energy deposition, Edep, in BGO, PbWO4, d15 for π^- with 10, 20, 50, 100, or 200 GeV energy, for 3 transverse sizes of crystals.

The effect of magnetic field to jet and di-jet mass reconstruction has been studied[10] using single W Monte Carlo events, with W momentum uniformly distributed between 0 and 100 GeV/c. Strong magnetific field induces a sizable contribution to di-jet mass resolution. The bending of charged particles in a 5T field affects the mass resolution larger than the the effect of the dual readout calorimeter energy resolution. The change of the invariant mass of a system in a magnetic field is calculable for each individual event using track trajectory and momentum, and the location and energy deposition at the impact point at the calorimeter, The correction for magnetic field is simple. In this short study, we do not repeat the magnetic field tracking correction study, we just show some results before and after the tracking correction. Much more detailed studies of jet and di-jet mass resolution should be done with more realistic simulation of the detector.

Dual Readout reconstructed Z mass (without jet clustering), for 5,000 $Z \rightarrow \text{jets}$ before and after tracking correction for B field are shown in Figure 9 for Z bosons with $P_t = 50, 100 \text{ GeV/c}$ and in Figure 10 for Z bosons with $P_t = 200 \text{ GeV/c}$. The over-correction in Figure 10 is also observed in Figure 20. More work is needed for crystal dual readout correction, for type(density) of crystal, GEANT4 physics list, and energy dependence. Dual Readout reconstructed W and Z mass (without jet clustering), for 5,000 $W \rightarrow \text{jets}$ and 5,000 $Z \rightarrow \text{jets}$ are shown in FIG. 11.

FIG. 9: BGO dual readout corrected Z mass, before (left) and after (right) tracking correction. Top: Z with $P_t = 50$ GeV/c. Bottom: Z with $P_t = 100$ GeV/c

FIG. 10: BGO dual readout corrected Z mass, before and after tracking correction, for Z with $P_t = 200$ GeV/c.

Jets	P	Mass	rms	M_corrected	rms
W_0_100	0-100	77.68	6.30	79.54	6.72
W_100_200	100-200	80.85	6.89	86.72	8.31
Z_0_100	0-100	86.58	8.64	88.21	8.86
Z_10-250	10-250	77.	6.	79.	6.
Z 30x30, 50x50	50	88.24	8.19	88.93	8.12
Z 30x30, 50x50	100	89.36	7.61	91.45	7.76
Z 30x30, 50x50	200	93.12	8.36	98.25	8.32
Z 15x15, 25x25	50	85.76	14.37	86.44	14.21
Z_0_100 15x15, 25x25	0-100	84.97	12.79	86.61	12.96
Z_0_100 30x30, 50x50	0-100	78.65	11.83	80.23.	11.99
Z_0_100 45x45, 75x75	0-100	78.56	11.84	80.19	12.01
W_0_100 15x15, 25x25	0-100	76.44	10.42	78.30	10.80
W_0_100 30x30, 50x50	0-100	70.90	9.47	72.77	9.82
W_0_100 45x45, 75x75	0-100	70.81	9.59	72.68	9.95

TABLE VII: W or Z mass from Dual Readout BGO Calorimeter CCAL02, from GEANT4 QGSP_BERT, before and after tracking correction for 5 Tesla B-field.

FIG. 11: Dual Readout reconstructed W and Z mass (without jet clustering), for 5,000 $W \rightarrow jets$ and 5,000 $Z \rightarrow jets$.

The relative number of W and/or Z events will depend on the physics processes at the future lepton collider. It is important to achieve the goal of $30\%/\sqrt{E}$ jet energy resolution.

Longitudinal segmentation of the dual readout crystal hadron calorimeter should be studied with more realistic simulation including light yields, photon detection efficiency, and support for the 700 tons of crystals.

V. SUMMARY

Studies of requirements and specifications of crystals are necessary to develop a new generation of crystals for dual readout crystal hadron or total absorption calorimeter. This has been a short and basic comparison study of PbWO₄ and BGO as candidates for Dual Readout Crystal hadron calorimeter. The cost of PbWO₄ is less prohibitive than BGO. A calorimeter with PbWO₄ would have more interaction lengths, for more hadron shower containment than with BGO. Hadron shower energy leakage is clearly observed for BGO with 5.8 interaction lengths and PbWO₄ with $7 \lambda_I$, but not for d15 and d20 crystals with densities of 15 g/cm³ or 20 g/cm³. With 5.8 or 7 interaction lengths, the hadron shower leakage significantly degrades the hadron energy resolution before and/or after dual readout correction. Calorimeters at the Muon Collider would require at least 8 interaction lengths.

The detector simulation should have more realistic geometry than the present CCAL02. The simulation should include boundaries between crystals including for the support structure for the 700 tons of crystals, and should simulate the photo-detectors and associated efficiencies. The simulation should enable varying longitudinal segmentation for the important longitudinal segmentation and calibration studies. More complete simulation with crystal Light Yield, Decay Time, digitization and optical readout efficiencies and noise will be needed for calibration and energy resolution studies of the feasibility of dual readout crystal total absorption or hadron calorimeter.

FIG. 12: Photon detection efficiency of MPPC/SiPM, including cross-talk and after-pulse (20-30% over-estimate).[16]
Light yields of crystals, Photon detection efficiency, longitudinal segmentation, crystal support structure, and more realistic geometry should be implemented in the simulation.

VI. ACKNOWLEDGMENTS

Thanks to Hans Wenzel and Adam Para for their important help with the dual readout crystal calorimeter simulation and analysis software for this study.

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-
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 John Hauptman, “Detector Design Strategies”,
<http://indico.fnal.gov/materialDisplay.py?contribId=67&sessionId=22&materialId=slides&confId=2855>
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 John Hauptman, “Dual Readout Calorimetry”,
<http://indico.fnal.gov/materialDisplay.py?contribId=31&sessionId=17&materialId=slides&confId=2855>
 Vito Di Benedetto, “Dual Readout Calorimetry in ILCROOT”,

<http://indico.fnal.gov/materialDisplay.py?contribId=32&sessionId=17&materialId=slides&confId=2855>
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<http://agenda.infn.it/getFile.py/access?resId=0&materialId=slides&confId=539>

VIII. APPENDIX A: ADDITIONAL PLOTS

FIG. 13: Simulation of 100 GeV π^- shower in the DREAM dual readout Calorimeter, which has 10 interaction lengths[4]

How many interaction length for HCAL?

ILD	SiD	4th
5.7 λ	4.5 λ	8.0 λ
ECAL $\sim 1 \lambda$		1.3 λ

	W	U	Fe
density [g/cm ³]	19.3	19.0	7.9
λ_{Int} [cm]	10.0	11.0	16.8
X_0 [cm]	0.3	0.3	1.8

Expl: to absorb 95% of the energy of a 300 GeV pion $\rightarrow 8 \lambda_I$

FIG. 14: Interaction Lengths for Hadron calorimeter[14]

FIG. 15: Typical Hadron shower in E594 neutrino interaction.[15] The calorimeter had 22 interaction lengths.

Crystals for HEP Calorimeters

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF ₂	BGO	LYSO(Ce)	PWO	PbF ₂
Density (g/cm ³)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (°C)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7	21.0
Refractive Index ^a	1.85	1.79	1.95	1.50	2.15	1.82	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence ^b (nm) (at peak)	410	550	420 310	300 220	480	402	425 420	?
Decay Time ^b (ns)	245	1220	30 6	650 0.9	300	40	30 10	?
Light Yield ^{b,c} (%)	100	165	3.6 1.1	36 4.1	21	85	0.3 0.1	?
d(LY)/dT ^b (%/°C)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	?
Experiment	Crystal Ball	BaBar BELLE BES III	KTeV	(L*) (GEM) TAPS	L3 BELLE	KLOE-2 SuperB SLHC?	CMS ALICE PANDA	HHCAL?

a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

FIG. 16: crystals for calorimeter[11]

FIG. 17: LCPhys 25_15 Cerenkov (left) and Scintillation (right) energy deposition. Top: 10 GeV e^- ; Bottom: 50 GeV e^-

IX. APPENDIX B: RESULTS FROM HANS WENZEL

FIG. 18: Leakage also observed by Hans Wenzel

FIG. 19: Leakage also observed by Hans Wenzel

FIG. 20: D15 Dual Readout corrected π^- energy, from Hans Wenzel
(compare with FIG. 21 for BGO)

FIG. 21: BGO Dual Readout corrected π^- energy, from Hans Wenzel
(compare with FIG. 20 for d15)

X. APPENDIX C: INTRODUCTORY COMPUTING INFO

To use SLIC, jas3 to study Dual Readout Crystal calorimeter :

<http://confluence.slac.stanford.edu/display/ilc/SLIC+Dual+Read+Out+Tutorial>

LCSim Tutorials :

<https://confluence.slac.stanford.edu/display/ilc/LCSim+Tutorials>

To use OSG Grid :

<http://confluence.slac.stanford.edu/display/ilc/How+do+I+use+the+OSG+Grid>

Obtain DOE Grid Certificate :

<http://security.fnal.gov/pki/Get-Personal-DOEGrids-Cert.html>

ILC VO Registration : <http://cd-amr.fnal.gov/ilc/ilcsim/ilcvo-registration.shtml>

Setting up Netbeans : <https://confluence.slac.stanford.edu/display/ilc/Setting+Up+Netbeans+6.5+with+Maven+2>

XI. APPENDIX D: ANALYSIS FRAMEWORK

This study is being performed on the `ilcsim.fnal.gov` computing cluster provided by the Fermilab Computing Division SSE Group. The analysis system is the Java Analysis Studio JAS3 <http://jas.freehep.org/jas3/> which is a general purpose, open-source, data analysis tool.

```
<ilcsim2.fnal.gov> source setup.sh

<ilcsim2> which jas3
alias jas3 = '/ilc/ild/gpyeh/jas3-0.8.3/jas3'
            /ilc/ild/gpyeh/jas3-0.8.3/jas3

// default on ilcsim.fnal.gov is jas3-0.8.2
ssh ilcsim.fnal.gov
<ilcsim> setup jas3
<ilcsim> which jas3
            /ilc/ild/gpyeh/jas3-0.8.2/jas3

<ilcsim> jas3 &

/* from Jas3 Menu */

/* to input a file */
File
  Open file
    /* select a file */
    /* e.g.
      /ild/ild/wenzel/ccal02/slciio_combined/
      LHEP_pi-10._130.slciio */

/* to input, compile, load, execute an analysis java script */
Help
  Examples
    org.lcsim Examples
      Analysis 101
        RightButton
          Compile
        RightButton
          Load

Click on the > arrow to run
```

- New simulation files for density & leakage study

```
<ilcsim2.fnal.gov> cd /ilc/ild/gpyeh/ccal02/slacio_combined
<ilcsim2.fnal.gov> ls -lh *.slcio
```

```
gpyeh  3.9G Nov 30 17:16 BERT__W_0_100GeV_25_15.slacio
gpyeh   97M Dec 12 15:13 concat_events.slacio
gpyeh  112M Nov 17 12:26 LCPhys_ccal02_25_15_e-_10.slacio
gpyeh  157M Nov 23 14:32 LCPhys_ccal02_25_15_e-_20.slacio
gpyeh  251M Nov 17 17:53 LCPhys_ccal02_25_15_e-_50.slacio
gpyeh  3.1G Nov 17 12:45 LCPhys_ccal02_25_15_pi-_100.slacio
gpyeh  683M Nov 17 12:30 LCPhys_ccal02_25_15_pi-_10.slacio
gpyeh  1.1G Nov 17 17:45 LCPhys_ccal02_25_15_pi-_20.slacio
gpyeh  2.0G Nov 17 12:38 LCPhys_ccal02_25_15_pi-_50.slacio
gpyeh  113M Nov 24 11:51 LCPhys_ccal02_75_45_e-_10.slacio
gpyeh  158M Nov 25 15:25 LCPhys_ccal02_75_45_e-_20.slacio
gpyeh  254M Nov 25 15:22 LCPhys_ccal02_75_45_e-_50.slacio
gpyeh  2.7G Nov 24 11:36 LCPhys_ccal02_75_45_pi-_100.slacio
gpyeh  694M Nov 25 15:06 LCPhys_ccal02_75_45_pi-_10.slacio
gpyeh  1.1G Nov 24 11:47 LCPhys_ccal02_75_45_pi-_20.slacio
gpyeh  2.0G Nov 25 15:16 LCPhys_ccal02_75_45_pi-_50.slacio
gpyeh  3.4G Dec 13 14:02 LCPhys_d10_50_30_pi-_100.slacio
gpyeh  712M Dec 13 13:52 LCPhys_d10_50_30_pi-_10.slacio
gpyeh  5.4G Dec 14 17:15 LCPhys_d10_50_30_pi-_200.slacio
gpyeh  1.1G Dec 13 13:59 LCPhys_d10_50_30_pi-_20.slacio
gpyeh  2.1G Dec 13 13:50 LCPhys_d10_50_30_pi-_50.slacio
gpyeh  3.3G Nov 29 22:02 LCPhys_d15_25_15_pi-_100.slacio
gpyeh  680M Nov 30 13:54 LCPhys_d15_25_15_pi-_10.slacio
gpyeh  1.1G Nov 30 13:48 LCPhys_d15_25_15_pi-_20.slacio
gpyeh  2.1G Nov 30 13:41 LCPhys_d15_25_15_pi-_50.slacio
gpyeh   52M Dec 12 15:25 LCPhys_d15_50_30_e-_10.slacio
gpyeh  133M Dec 12 15:26 LCPhys_d15_50_30_e-_50.slacio
gpyeh  3.3G Dec  2 12:07 LCPhys_d15_50_30_pi-_100.slacio
gpyeh  683M Dec  2 13:56 LCPhys_d15_50_30_pi-_10.slacio
gpyeh  5.2G Dec  3 11:30 LCPhys_d15_50_30_pi-_200.slacio
gpyeh  1.1G Dec  2 13:57 LCPhys_d15_50_30_pi-_20.slacio
gpyeh  2.1G Dec  2 12:12 LCPhys_d15_50_30_pi-_50.slacio
gpyeh  3.3G Nov 30 12:30 LCPhys_d15_75_45_pi-_100.slacio
gpyeh  680M Nov 30 14:25 LCPhys_d15_75_45_pi-_10.slacio
gpyeh  1.1G Nov 30 13:51 LCPhys_d15_75_45_pi-_20.slacio
gpyeh  2.1G Nov 30 13:11 LCPhys_d15_75_45_pi-_50.slacio
gpyeh  3.0G Nov 23 21:10 LCPhys_d20_25_15_pi-_100.slacio
gpyeh  631M Nov 24 11:58 LCPhys_d20_25_15_pi-_10.slacio
gpyeh  985M Nov 25 14:04 LCPhys_d20_25_15_pi-_20.slacio
gpyeh  1.9G Nov 25 14:09 LCPhys_d20_25_15_pi-_50.slacio
gpyeh  3.0G Nov 30 15:31 LCPhys_d20_50_30_pi-_100.slacio
gpyeh  633M Nov 30 15:35 LCPhys_d20_50_30_pi-_10.slacio
gpyeh  4.8G Dec  3 11:34 LCPhys_d20_50_30_pi-_200.slacio
gpyeh  987M Nov 30 15:34 LCPhys_d20_50_30_pi-_20.slacio
gpyeh  1.9G Nov 30 15:33 LCPhys_d20_50_30_pi-_50.slacio
gpyeh  3.0G Nov 30 15:20 LCPhys_d20_75_45_pi-_100.slacio
gpyeh  632M Nov 30 14:40 LCPhys_d20_75_45_pi-_10.slacio
gpyeh  989M Nov 30 14:42 LCPhys_d20_75_45_pi-_20.slacio
gpyeh  1.9G Nov 30 15:18 LCPhys_d20_75_45_pi-_50.slacio
gpyeh  114M Dec 12 15:22 LCPhys_d7_50_30_e-_10.slacio
gpyeh  254M Dec 12 15:20 LCPhys_d7_50_30_e-_50.slacio
gpyeh  3.2G Dec  1 15:22 LCPhys_d7_50_30_pi-_100.slacio
```

```

gpyeh 691M Dec 1 15:26 LCPhys_d7_50_30_pi-_10.slcio
gpyeh 5.0G Dec 3 11:26 LCPhys_d7_50_30_pi-_200.slcio
gpyeh 1.1G Dec 1 15:25 LCPhys_d7_50_30_pi-_20.slcio
gpyeh 2.0G Dec 1 15:24 LCPhys_d7_50_30_pi-_50.slcio
gpyeh 3.3G Dec 1 14:36 LCPhys_d8_25_15_pi-_100.slcio
gpyeh 708M Dec 1 14:50 LCPhys_d8_25_15_pi-_10.slcio
gpyeh 1.1G Dec 1 14:43 LCPhys_d8_25_15_pi-_20.slcio
gpyeh 2.1G Dec 1 14:42 LCPhys_d8_25_15_pi-_50.slcio
gpyeh 97M Dec 12 15:17 LCPhys_d8_50_30_e-_10.slcio
gpyeh 221M Dec 12 15:19 LCPhys_d8_50_30_e-_50.slcio
gpyeh 3.3G Dec 1 15:03 LCPhys_d8_50_30_pi-_100.slcio
gpyeh 709M Dec 1 14:54 LCPhys_d8_50_30_pi-_10.slcio
gpyeh 5.2G Dec 3 11:21 LCPhys_d8_50_30_pi-_200.slcio
gpyeh 1.1G Dec 1 14:59 LCPhys_d8_50_30_pi-_20.slcio
gpyeh 2.1G Dec 1 15:01 LCPhys_d8_50_30_pi-_50.slcio
gpyeh 3.3G Dec 1 15:10 LCPhys_d8_75_45_pi-_100.slcio
gpyeh 708M Dec 1 15:13 LCPhys_d8_75_45_pi-_10.slcio
gpyeh 1.1G Dec 1 15:12 LCPhys_d8_75_45_pi-_20.slcio
gpyeh 2.1G Dec 1 15:11 LCPhys_d8_75_45_pi-_50.slcio
gpyeh 3.9G Nov 30 16:09 LCPhys_W_0_100GeV_25_15.slcio
gpyeh 119M Nov 20 15:47 QGSP_BERT_ccal02_25_15_e-_10.slcio
gpyeh 170M Nov 21 12:16 QGSP_BERT_ccal02_25_15_e-_20.slcio
gpyeh 281M Nov 20 17:55 QGSP_BERT_ccal02_25_15_e-_50.slcio
gpyeh 2.3G Nov 19 16:35 QGSP_BERT_ccal02_25_15_pi-_100.slcio
gpyeh 768M Nov 19 16:30 QGSP_BERT_ccal02_25_15_pi-_10.slcio
gpyeh 1.1G Nov 21 12:18 QGSP_BERT_ccal02_25_15_pi-_20.slcio
gpyeh 1.7G Nov 21 12:22 QGSP_BERT_ccal02_25_15_pi-_50.slcio
gpyeh 2.1G Dec 19 14:08 W_0_100_d15_25_15_BERT.slcio
gpyeh 2.1G Dec 19 13:56 W_0_100_d15_50_30_BERT.slcio
gpyeh 3.9G Dec 6 20:48 W_0_100GeV_25_15_BERT.slcio
gpyeh 3.3G Nov 23 14:55 W_0_100GeV_25_15.slcio
gpyeh 3.9G Dec 18 12:52 W_0_100GeV_50_30_BERT.slcio
gpyeh 3.9G Dec 15 12:13 W_0_100GeV_75_45_BERT.slcio
gpyeh 8.0G Dec 18 14:39 WZ_0_100GeV_25_15_BERT.slcio
gpyeh 8.1G Dec 18 14:03 WZ_0_100GeV_50_30_BERT.slcio
gpyeh 6.8G Dec 18 15:33 WZ_0_100GeV_Para.slcio
gpyeh 2.3G Dec 19 14:09 ZO_0_100_d15_25_15_BERT.slcio
gpyeh 2.3G Dec 19 13:54 ZO_0_100_d15_50_30_BERT.slcio
gpyeh 4.2G Dec 6 20:44 ZO_0_100GeV_25_15_BERT.slcio
gpyeh 3.3G Nov 23 16:17 ZO_0_100GeV_25_15_LCPhys.slcio
gpyeh 4.2G Dec 18 13:41 ZO_0_100GeV_50_30_BERT.slcio
gpyeh 4.2G Dec 15 11:57 ZO_0_100GeV_75_45_BERT.slcio
gpyeh 6.5G Nov 18 12:42 ZO_50GeV_25_15_BERT.slcio
gpyeh 5.5G Nov 23 15:29 ZO_50GeV_25_15_LCPhys.slcio
gpyeh 5.5G Nov 16 15:16 ZO_50GeV_25_15.slcio
gpyeh 27M Nov 12 15:46 ZO_50GeV_25_15_s.slcio

```

<ilcsim2.fnal.gov>

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ls -lt /ilc/sid/wenzel/ccal02/slciocombined/LCPhys_PbW04_*
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4190475160 LCPhys_PbW04_pi-_100._130.slcio
2624083292 LCPhys_PbW04_pi-_50._130.slcio
1370850472 LCPhys_PbW04_pi-_20._130.slcio
896542732 LCPhys_PbW04_pi-_10._130.slcio
625596460 LCPhys_PbW04_pi-_5._130.slcio

```

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310799388 LCPhys_PbW04_pi-2._130.slcio
180056960 LCPhys_PbW04_pi-1._130.slcio

38868620 LCPhys_PbW04_e-100._130.slcio
250532416 LCPhys_PbW04_e-50._130.slcio
150054672 LCPhys_PbW04_e-20._130.slcio
103844768 LCPhys_PbW04_e-10._130.slcio
73020576 LCPhys_PbW04_e-5._130.slcio
46439176 LCPhys_PbW04_e-2._130.slcio
33169756 LCPhys_PbW04_e-1._130.slcio

```

```
ls -lt /ilc/sid/wenzel/ccal02/slciocombined/
```

```

6619106004 LCPhys_pi-100._130.slcio
4189314336 LCPhys_pi-50._130.slcio

```

- Previously already available simulation files

```
ls -lt /ilc/ild/wenzel/ccal02/slciocombined/LCPhys_*
```

```

163995036 LCPhys_e-20._130.slcio
116691408 LCPhys_e-10._130.slcio
83183400 LCPhys_e-5._130.slcio
53196556 LCPhys_e-2._130.slcio
38006960 LCPhys_e-1._130.slcio

1100666692 LCPhys_pi-20._130.slcio
712907964 LCPhys_pi-10._130.slcio
497708828 LCPhys_pi-5._130.slcio
253194264 LCPhys_pi-2._130.slcio
147155696 LCPhys_pi-1._130.slcio

```

```
/ilc/ild/wenzel/ccal02/slciocombined/
```

```

QGSP_pi-20._130.slcio
QGSP_pi-10._130.slcio

```

```

QGSP_BERT_pi-20._130.slcio
QGSP_BERT_pi-10._130.slcio

```

```

QGSC_pi-20._130.slcio
QGSC_pi-10._130.slcio

```

```

LHEP_pi-20._130.slcio
LHEP_pi-10._130.slcio

```

```

LCPhys_pi-20._130.slcio
LCPhys_pi-10._130.slcio

```

```
pi_Theta90_100GeV.slcio
```

```
pi_Theta90_50GeV.slcio
pi_Theta90_20GeV.slcio
pi_Theta90_10GeV.slcio
```

```
QGSP_BERT_e-20._130.slcio
QGSP_BERT_e-10._130.slcio
```

```
LCPhys_e-20._130.slcio
LCPhys_e-10._130.slcio
```

```
electron_Theta90_100GeV.slcio
electron_Theta90_50GeV.slcio
electron_Theta90_20GeV.slcio
electron_Theta90_10GeV.slcio
```

Other Monte Carlo Sample Files:

```
/ilc/ild/wenzel/ccal02/slciocombined/*
/ilc/sid/wenzel/ccal02/slciocombined/LCPhys_PbW04_*
/ilc/sid/wenzel/ccal02/aida/
/ilc/ild/para/results/*
```

Monte Carlo Sample java codes

```
AnalyzeDualRO.java      from Hans Wenzel
MCMCPrimaM1M3.java      from Adam Para
```

Adam Para's files: /ilc/ild/para/results/

```
optical_LCPhys_BG0_d7.13_n2.15_pi-100.slcio
```

```
optical_QGSP_BERT_BG0_d7.13_n2.15_pi-100.slcio
optical_QGSP_BERT_BG0_d8.0_n2.21_pi-100.slcio
```

```
fine_QGSP_BERT_BG0_d15.0_n2.15_pi-100.0_0_B5.0.slcio
fine_QGSP_BERT_BG0_d7.13_n2.15_pi-100.0_0_B5.0.slcio
```

```
fine_QGSP_BERT_BG0_d7.13_n2.15_pi-100.0_0_B3.0.slcio
fine_QGSP_BERT_BG0_d7.13_n2.15_pi-100.0_0_B0.0.slcio
```

```
fine_QGSP_BERT_BG0_d15.0_n2.15_pi-100.0_0_B0.0.slcio
```

```
jets_1.0.stdhep -> W_Theta90_0_100Gev.stdhep
jets_2.0.stdhep -> W_Theta90_100_200Gev.stdhep
jets_3.0.stdhep -> Z0_Theta90_0_100Gev.stdhep
jets_4.0.stdhep -> Z0_Theta90_10-250GeV.stdhep
```

```
jets_5.0.stdhep -> Z0_Theta90_50GeV.stdhep
jets_6.0.stdhep -> Z0_Theta90_100GeV.stdhep
jets_7.0.stdhep -> Z0_Theta90_200GeV.stdhep
```

```
ls -lt /ilc/ild/para/results/*jets_*B5*
```

```
fine_QGSP_BERT_BG0_d7.13_n2.15_jets_5.0_B5.0.slcio  Z0_50GeV
fine_QGSP_BERT_BG0_d7.13_n2.15_jets_6.0_B5.0.slcio  Z0_100GeV
fine_QGSP_BERT_BG0_d7.13_n2.15_jets_7.0_B5.0.slcio  Z0_200GeV
```


- stdhep files to generate W or Z events

```
<ilcsim.fnal.gov> ls -lt /ilc/ild/wenzel/ccal02/stdhep/Z0_*.stdhep  
W_*.stdhep
```

```
<ilcsim.fnal.gov> ls -lt /ilc/ild/gpyeh/stdhep/  
total 1319936  
450714296 Nov  6  Z0_Theta90_200GeV.stdhep  
450426680 Nov  6  Z0_Theta90_100GeV.stdhep  
450440504 Nov  6  Z0_Theta90_50GeV.stdhep
```

- aida files

```
<ilcsim2.fnal.gov> ls -lh          /ilc/ild/gpyeh/aida
total 19M
 726K Nov 18 15:21 LCPhys_ccal02_25_15_e-_10.aida
 725K Nov 18 15:28 LCPhys_ccal02_25_15_e-_50.aida
 891K Nov 17 15:59 LCPhys_ccal02_25_15_pi-_100.aida
 902K Nov 17 14:09 LCPhys_ccal02_25_15_pi-_10.aida
 903K Nov 17 14:52 LCPhys_ccal02_25_15_pi-_50.aida
 749K Nov 30 21:08 LCPhys_ccal02_75_45_pi-_100.aida
 919K Nov 30 22:28 LCPhys_ccal02_75_45_pi-_10.aida
 896K Nov 30 22:05 LCPhys_ccal02_75_45_pi-_20.aida
 861K Nov 30 21:18 LCPhys_ccal02_75_45_pi-_50.aida
 850K Nov 25 17:09 LCPhys_ccal02_d20_25_15_pi-_100.aida
 832K Nov 27 17:15 LCPhys_ccal02_d20_25_15_pi-_10.aida
 840K Nov 27 16:50 LCPhys_ccal02_d20_25_15_pi-_20.aida
 855K Nov 27 15:48 LCPhys_ccal02_d20_25_15_pi-_50.aida
 812K Nov 29 23:56 LCPhys_d15_25_15_pi-_100.aida
 859K Dec  1 12:42 LCPhys_d15_25_15_pi-_10.aida
 859K Nov 30 16:37 LCPhys_d15_25_15_pi-_20.aida
 856K Nov 30 14:55 LCPhys_d15_25_15_pi-_50.aida
 854K Nov 30 13:54 LCPhys_d15_75_45_pi-_100.aida
 851K Nov 30 16:00 LCPhys_d15_75_45_pi-_50.aida
 729K Nov 18 17:32 LCPhys_e-_10_130.aida
   621 Oct 29 16:51 numbers.txt
 731K Nov 18 17:37 QGSP_BERT_e-_10_130.aida
 412K Nov 18 14:46 Z0_50GeV_25_15_BERT.Histograms
 403K Nov 16 16:15 Z0_BGO_50_25_15_Historgrams
```

```
-----

ls -lh /ilc/sid/wenzel/ccal02/aida/
```

```
<ilcsim2.fnal.gov> ls -lh /ilc/sid/wenzel/ccal02/aida/
total 48M
  wenzel 260K Nov  3  BGO_digis_pi-_200_resol.aida
  wenzel 7.9M Nov  9  LCPhys_ccal02_d15_digis_pi-_all.aida
  wenzel 5.1K Oct 28  LCPhys_digis_e-_10.aida
  wenzel 27K Oct 28  LCPhys_digis_e-_all.aida
  wenzel 9.8M Oct 28  LCPhys_digis_pi-_all.aida
  wenzel 3.5M Oct 28  LCPhys_digis_pi-_all_resol.aida
  wenzel 29K Oct 28  LCPhys_e-_all_130.aida
  wenzel 2.0K Oct 28  LCPhys_PbW04_e-_all_130.aida
  wenzel 28K Oct 28  LCPhys_PBW0_digis_e-_all.aida
  wenzel 8.6M Oct 28  LCPhys_PbW0_digis_pi-_all.aida
  wenzel 1.4M Oct 28  LCPhys_pi-_all_130.aida
  wenzel 426K Nov  3  PBW04_digis_pi-_200_resol.aida
  wenzel 2.6M Oct 28  PBW0_digis_pi-_all_resol.aida
  wenzel 20K Oct 28  QGSP_BERT_digis_e-_all.aida
  wenzel 8.1M Oct 28  QGSP_BERT_digis_pi-_all.aida
  wenzel 3.3M Oct 28  QGSP_BERT_digis_pi-_all_resol.aida
  wenzel 1.8M Oct 28  QGSP_BERT_HP_ccal02_pi-_all_130.aida
```

XII. APPENDIX E: SIMULATION MODIFICATION FROM BGO TO PBW04

```
// From Hans' desktop: copy ccal02 from ilcsim.fnal.gov:
scp -r ilcsim.fnal.gov:/ilc/ild/wenzel/ccal02/ccal02/ .

mv ccal02 ccal02_PbW04
cd ccal02_PbW04/

// Modify ccal02.xml
emacs ccal02.xml &
ls ~/NetBeansProjects/GeomConverter/target/bin

// Modify these files
emacs ccal02_PbW04.lcdd &
emacs ccal02.lcdd &
emacs compact.xml &
emacs ccal02_PbW04.xml &
emacs compact.xml
cd ..

// Copy to ilcsim.fnal.gov:
scp -r ccal02_PbW04/ ilcsim.fnal.gov:/ilc/ild/wenzel/ccal02/

// to change transverse Segmentation, e.g.
//      from 50 x 50, 30 x 30 -> 25 x 25, 15 x 15
// or/and to change density, or B_Field

cd /ilc/ild/gpyeh/ccal02/DetectorGeneration/

Invoke convert.csh from Adam Para and Hans Wenzel
with the parameters

set detector = $1
set material = $2
set density = $3
set refind = $4
set had_segm = $5
set em_segm = $6
set bfield = $7

<ilcsim2.fnal.gov> which tcsh
/bin/tcsh
<ilcsim2.fnal.gov>

<ilcsim.fnal.gov> which tcsh
/usr/local/bin/tcsh
<ilcsim.fnal.gov> nedit convert.csh

The command to create the zip file for ccal02 geometry
with BGO and 15. density is:
./convert.csh ccal02_d15 BGO 15. 1.63 50 30 5.

./convert.csh ccal02_25_15 BGO 7.13 2.15 25 15 5.
./convert.csh ccal02_75_45 BGO 7.13 2.15 75 45 5.
./convert_ilcsim.csh ccal02_d20_50_30 BGO 20. 2.15 50 30 5.
```

```
./convert_ilcsim2.csh ccal02_d7_50_30 BGO 7.13 2.15 50 30 5.
./convert_ilcsim2.csh ccal02_d8_50_30 BGO 8.3 2.15 50 30 5.
```

```
<ilcsim2.fnal.gov> ls -lt /ilc/ild/gpyeh/ccal02/DetectorGeneration/*.lcdd
```

```
Nov 28 ccal02_d15_25_15.lcdd
Nov 28 ccal02_d15_50_30.lcdd
Nov 28 ccal02_d15_75_45.lcdd

Nov 23 ccal02_d20_25_15.lcdd
Nov 28 ccal02_d20_50_30.lcdd
Nov 28 ccal02_d20_75_45.lcdd

Nov 28 ccal02_PbW04_25_15.lcdd
Nov 28 ccal02_PbW04_75_45.lcdd

Nov 23 ccal02_75_45.lcdd
Nov 11 ccal02_25_15.lcdd
```

.zip must be copied to the ~/.lcsim/cache for jas and lcsim to pick it up.

```
cp http%3A%2F%2Fwww.lcsim.org%2Fdetectors%2Fccal02_d15.zip ~/.lcsim/cache
```

```
-----
<ilcsim.fnal.gov> ls -lt ~/.lcsim/cache
```

```
  /home2/ilc/gpyeh/.lcsim/cache
Nov 12 http%3A%2F%2Fwww.lcsim.org%2Fdetectors%2Fccal02_25_15.zip
Oct 22 http%3A%2F%2Fwww.lcsim.org%2Fdetectors%2Fccal02.zip
Nov 23 http%3A%2F%2Fwww.lcsim.org%2Fdetectors%2Fccal02_75_45.zip
Nov 28 http%3A%2F%2Fwww.lcsim.org%2Fdetectors%2Fccal02_d15_25_15.zip
Nov 28 http%3A%2F%2Fwww.lcsim.org%2Fdetectors%2Fccal02_d15_50_30.zip
Nov 28 http%3A%2F%2Fwww.lcsim.org%2Fdetectors%2Fccal02_d15_75_45.zip
Nov 23 http%3A%2F%2Fwww.lcsim.org%2Fdetectors%2Fccal02_d20_25_15.zip
Nov 28 http%3A%2F%2Fwww.lcsim.org%2Fdetectors%2Fccal02_d20_50_30.zip
Nov 28 http%3A%2F%2Fwww.lcsim.org%2Fdetectors%2Fccal02_d20_75_45.zip
Nov 28 http%3A%2F%2Fwww.lcsim.org%2Fdetectors%2Fccal02_PbW04_25_15.zip
Nov 28 http%3A%2F%2Fwww.lcsim.org%2Fdetectors%2Fccal02_PbW04_75_45.zip
```

get \${detector}.lcdd and the corresponding zip file.

The segmentation in EM and Had sections is in transverse plane only.

Units are mm. Bfield in tesla.

```
unzip http%3A%2F%2Fwww.lcsim.org%2Fdetectors%2Fccal02_25_15.zip
```

```
<ilcsim.fnal.gov> ls -lt /ilc/ild/gpyeh/grid_gp_d15
```

```
Nov 17 slic_grid_Z0_50GeV_25_15_BERT.run
Nov 17 slic_grid_Z0_50GeV_25_15_BERT.csh
Nov 12 slic_grid_Z0_50GeV_25_15.run
```

```

Nov 12  slic_grid_Z0_50GeV_25_15.csh
Nov  6  slic_grid_Z0_50GeV_d15.run
Nov  6  slic_grid_Z0_50GeV_d15.csh
    584 Nov  6  slic_grid_Z0_Theta90_50GeV.run
    675 Nov  6  slic_grid_Z0_Theta90_50GeV.csh
192512 Nov  5  stderr
192512 Nov  5  stdout
192512 Nov  5  log
    736 Nov  5  run_slic_grid
    2036 Nov  5  my_run_slic_grid.csh
    1581 Nov  4  my_slic.csh

```

```

ls -lt /ilc/ild/wenzel/ccal02/*/*.csh
    2036 Nov  5  /ilc/ild/wenzel/ccal02/grid_gp_ccald15/my_run_slic_grid.csh
    1581 Nov  5  /ilc/ild/wenzel/ccal02/grid_gp_ccald15/my_slic.csh
    2042 Nov  4  /ilc/ild/wenzel/ccal02/grid_gp_d15/my_run_slic_grid.csh
    1581 Nov  4  /ilc/ild/wenzel/ccal02/grid_gp_d15/my_slic.csh
    2038 Oct 26  /ilc/ild/wenzel/ccal02/grid_gp/my_run_slic_grid.csh
    1581 Oct 26  /ilc/ild/wenzel/ccal02/grid_gp/my_slic.csh

```

```

ls -lt /ilc/ild/wenzel/ccal02/*/*.lcdd
975971 Nov  5  /ilc/ild/wenzel/ccal02/convert/ccal02_d15.lcdd
975971 Nov  5  /ilc/ild/wenzel/ccal02/ccal02_d15/ccal02_d15.lcdd
48840 Nov  5  /ilc/ild/wenzel/ccal02/ccal02_d15/ccal02_d15.xml
73571 Nov  4  /ilc/ild/wenzel/ccal02/ccal02_d15/ccal02_d15.heprep

994647 Nov  4  /ilc/ild/wenzel/ccal02/ccal02_PbW04_d15/ccal02_PbW04_d15.lcdd

994711 Oct 27  /ilc/ild/wenzel/ccal02/ccal02_PbW04/ccal02.lcdd
994646 Oct 27  /ilc/ild/wenzel/ccal02/ccal02_PbW04/ccal02_PbW04.lcdd

```

```

cd /ilc/ild/gpyeh/grid_gp_d15

```

```

Z0_50GeV_25_15_BERT.csh
  /lcdd/url  /ilc/ild/gpyeh/ccal02/DetectorGeneration/ccal02_25_15.lcdd

```

```

Z0_50GeV_25_15.csh
  /lcdd/url  /ilc/ild/gpyeh/ccal02/DetectorGeneration/ccal02_25_15.lcdd

```

```

Z0_50GeV_d15.csh
  /lcdd/url  /ilc/ild/gpyeh/ccal02/ccal02_PbW04_d15/ccal02_PbW04_d15.lcdd

```

```

Z0_50GeV_PbW04.csh
  /lcdd/url  /ilc/ild/gpyeh/ccal02/ccal02_PbW04_d15/ccal02_PbW04.lcdd

```

XIII. APPENDIX F: USING OSG GRID

```
// DOE Grid Certificate

ls *.p12
mkdir .globus
mv *.p12 .globus/

cd .globus

openssl pkcs12 -in mycert.p12 -clcerts -nokeys -out $HOME/.globus/usercert.pem
ls
openssl pkcs12 -in mycert.p12 -nocerts -out $HOME/.globus/userkey.pem

cd ..
chmod go-rw $HOME/.globus/userkey.pem
source /fnal/ups/grid/setup.sh
voms-proxy-init -valid 72:00 -voms ilc:/ilc/ild

-----

cd /ilc/ild/gpyeh/ccal02/grid_gp_d15/

// Setup the Grid Tools
source /fnal/ups/grid/setup.sh
// Session Certificate and quotas
voms-proxy-init -valid 72:00 -voms ilc:/ilc/ild
// To check the status of the proxy:
voms-proxy-info -all
ls

// to submit to grid to simulate Single particles
./my_slic.csh 10 e- 10. 100 130.0 0. 0. 1. 0. 0. LCPhys ccal02_PbW04.lcdd
./my_slic.csh 100 pi- 100. 100 130.0 0. 0. 1. 0. 0. LCPhys ccal02_d15_25_15.lcdd
./my_slic.csh 100 pi- 100. 100 130.0 0. 0. 1. 0. 0. LCPhys ccal02_d15_75_45.lcdd

ls -lt /ilc/ild/gpyeh/ccal02/grid_gp_d15/log/
ls -l stdout
ls -l stderr
condor_q owner gpyeh

// to submit to grid to simulate Z sample
// change .csh nevents = 100
// change .run queue 100
// condor_submit .run
condor_submit slic_grid_Z0_50GeV_25_15.run

// other condor commands
// condor_rm -all
// condor_release -all

=====
```

Date: Tuesday, Dec. 1, 2009

From: Gratia Operation <gratia-operation@opensciencegrid.org>

OSG metrics for VO ILC for November, 2009-11-01 to 2009-11-30

CN	Site	VO:Reporting Name	Job Success?	# Jobs	Wall Time (h)
G. P. Yeh	FNAL_GPGRID_1	ILC:ilc	Yes	6581	10318.5
G. P. Yeh	FNAL_GPGRID_1	ILC:ilddat	Yes	269	533.5
G. P. Yeh (all)		ALL		6850	10852.0

OSG metrics for VO ILC for December, 2009-12-01 to 2009-12-31

CN	Site	VO:Reporting Name	Job Success?	# Jobs	Wall Time (h)
G. P. Yeh	FNAL_GPGRID_1	ILC:ilc	Yes	4657	13366.6
G. P. Yeh	FNAL_GPGRID_1	ILC:ilddat	Yes	127	558.5
G. P. Yeh (all)		ALL		4784	13925.1

```

-----

cd /ilc/ild/gpyeh/
cp -r /ilc/ild/wenzel/ccal02/grid_gp_d15 .
cp -r /ilc/ild/wenzel/ccal02/ccal02_PbW04_d15 .
ls
gpyeh      2048 Nov  4 19:10 grid_gp_d15
gpyeh      2048 Nov  4 17:37 ccal02
gpyeh      4096 Nov  4 17:28 ccal02_PbW04_d15
gpyeh      2048 Oct 29 14:57 jas3-0.8.3
gpyeh 7349484 Oct 29 14:57 jas3-Linux-0.8.3.tar.gz
gpyeh      2048 Oct 29 14:49 NetBeansProjects
gpyeh      4096 Oct 29 14:15 netbeans-6.7.1
gpyeh      2048 Feb  9 2009 apache-maven-2.0.10

ls -lt /ilc/ild/gpyeh/grid_gp_d15
-rwxr-xr-x gpyeh      683 Nov 11 12:44 slic_grid_Z0_50GeV_25_15.csh
gpyeh      605 Nov  9 15:01 slic_grid_Z0_50GeV_25_15.run
gpyeh 192512 Nov  4 17:39 stderr
gpyeh 192512 Nov  4 17:39 stdout
gpyeh 192512 Nov  4 17:39 log

ls -lt /ilc/ild/gpyeh/ccal02
gpyeh      2048 Nov 11 17:21 slcio
gpyeh      4096 Nov 11 16:47 DetectorGeneration
gpyeh      2048 Nov 11 14:32 slcio_combined

```

```

gpyeh 2048 Nov 11 12:35 ccal02_25_15
gpyeh 2048 Nov 11 11:13 convert
gpyeh 4096 Nov 6 17:42 ccal02_PbW04_d15
gpyeh 2048 Nov 6 16:38 ccal02_PbW04

-----

// lcio concat combine slcio files

cd /ilc/ild/gpyeh/ccal02/slcio_combined/

cd /grid/app/CherSimDist_may2009/SimDist/packages/lcio/HEAD/
source setup.sh
//      which lcio

cd -
pwd
    /ilc/ild/gpyeh/ccal02/slcio_combined/

ls -l /ilc/ild/gpyeh/ccal02/slcio/LCPhys_ccal02_25_15.lcdd_e-*.slcio >
                                           combine_e10.txt
ls -l /ilc/ild/gpyeh/ccal02/slcio/LCPhys_ccal02_25_15.lcdd_pi-10*.slcio >
                                           combine_pi10.txt

// the following gets /bin/sh error on ilcsim.fnal.gov
//      It works on ilcsim2.fnal.gov

lcio concat -i combine.txt -o Z0_50GeV_25_15.slcio
lcio concat -i combine_d15_25_15_pi100.txt -o LCPhys_d15_25_15_pi-100.slcio

ls -lh
gpyeh 3319780264 Nov 17 LCPhys_ccal02_25_15_pi-100.slcio
gpyeh 2098802104 Nov 17 LCPhys_ccal02_25_15_pi-50.slcio
gpyeh 715474196 Nov 17 LCPhys_ccal02_25_15_pi-10.slcio
gpyeh 116763700 Nov 17 LCPhys_ccal02_25_15_e-10.slcio
gpyeh      7990 Nov 17 combine_pi50.txt
gpyeh      8090 Nov 17 combine_pi100.txt
gpyeh      7990 Nov 17 combine_pi10.txt
gpyeh      7890 Nov 17 combine_e10.txt
gpyeh 27368648 Nov 12 Z0_50GeV_25_15_s.slcio
gpyeh      255 Nov 12 combine.txt

ls -lh ../slcio

rm -f /ilc/ild/gpyeh/ccal02/slcio/LCPhys_ccal02_25_15.lcdd_pi-10*.slcio

```