The analysis of primex test run on September 15

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Abstract

Here we report the results of beamtest run in hallB about the energy energy resolution, coordinate resolution and rate dependece of lead tungstate crystals($PbWO_4$). These crystals are manufactured in Bogoroditsk of Russian and in Shanghai of China, respectively. This test run was performed in HallB of Jlab on september 15 2001 with tagged photon. In present beamtest run, high energy resolution of 1.15% was achieved to detector 4GeV electron.

1 Introduction

Lead tungstate $PbWO_4$ becomes recently well known as fast, dense and highly radiation resistant inorganic scintillator material[1,2,3,4]and is very suitable for the new generation of compact homogeneous calorimeter as to be constructed for high energy detectors CMS or ALICE for LHC[5]. Approved experiment Primex in HallB of CEBAF also planned to employee 480 modules of lead tungstate crystals of size $2.05 \times 2.05 \times 21.2$ cm^3 as an insertion in the center of the Hybrid Shower Calorimeter(HYCAL) which is expected to detect the photons from π^0 decay. The crystal insertion is surposed to significantly improve energy resolution, coordinate resolution and the radiation hardness of the HYCAL. The general goal of this beamtest run was to study the performance of lead tungstate crystals produced in Russia and China to set up specification for purchasing crystals, confirm HYCAL's energy and position resolution predictions for the current energy region of Primex, understand the rate dependence of gain.

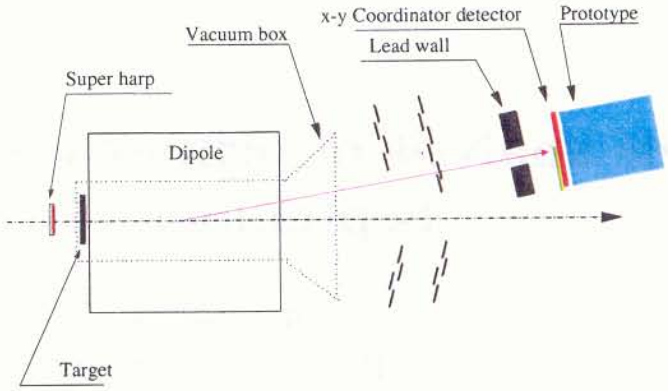

Figure 1: Sketch of experimental setup

2 Detector setup

The Jlab accelerator is capable to provide us electron beams with energy up to 6 GeV. The photon tagger in Jlab Hall B will be used at an eletron beam of 6 GeV to give the photon energy energies from 4.6 GeV to 5.7 GeV. The photons hit the converter and were converted to electrons.The Dipole (next to converter) bent the electrons to prototype to measure its energy resolution, coordinate resolutrion and rate dependence of gain. The high stable magnet field in Diploe guaranteed the electron energy resolution after Diploe is better than 0.1

6×6 array of lead tungstate crystals consists of our prototype and was installed inside a thermostatically controlled and optically isolated box. Since $PbWO_4$ light yield strongly depends on temperature of crystal, the temperature was controlled around 2 degrees with good stability to eliminate the effects of temperature variation. In plot 2, each square conceptully represents one crsytal which was wrapped by the aluminum. The number greater than 400 hundred in the square is run number. We moved the prototype so that electrons passing through the center of x-y coordinator can roughly hit the center of concerned crystal which is labelled by number less than 100 hundred in the square. The first 18 crystals are Russian and the other 18 are Chinese. We arranged the crystals in this way so that we can check the Chinese and Russian crystal performence independently. For all the runs shown in the squares, the event rate is around 1.5 kHz.

3 Experimental results

3.1 Energy calibration

To do the analysis, the first thing we need to do is the energy calibration. Since there is a x-y coordinator detector in front of prototype. The electrons were bent to the prototype by the Diploe. With the knowledge of Dipole's field and

424 1	2	425 3	4	426 5	6
423 7	8	422 9	10	427 11	12
420 13	14	419 15	16	418 17	18
414 19	20	413 21	22	412 23	24
409 25	26	410 27	28	411 29	30
415 31	32	416 33	34	417 35	36

Russian Crystals: 1-18
Chinese Crystals: 19-36

Figure 2: The arrangement of crystals in prototype.

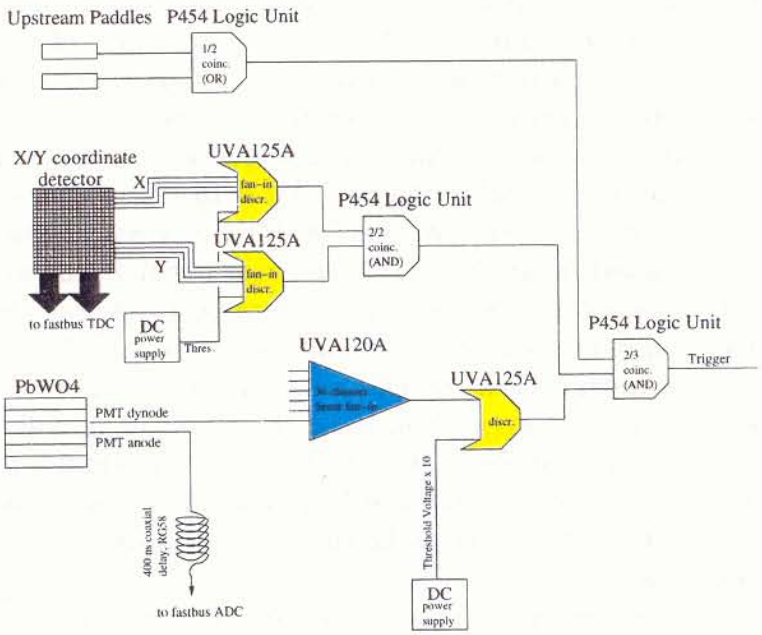

Figure 3: DAQ diagram

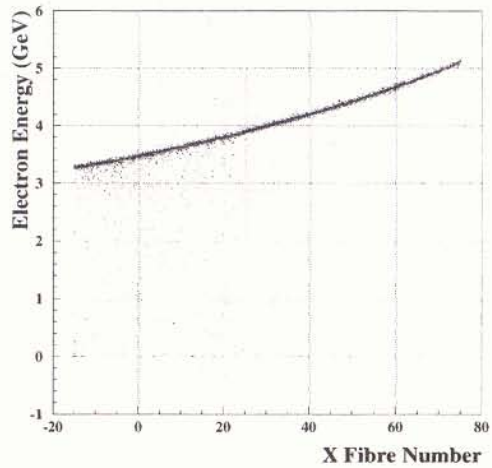

Figure 4: The simulated relationship between electron energy and x fibre number

bending angle, you can calculate the energy of electrons which pass through the x-y coordinator detector and hit the prototype. With surveying, you can easily konw the relationship between bending angle and x fibre number. Plot 4 here shows the energy of electron emerging out of Dipole as a function of x fibre number. This function was got by simulation with Giant3. The region between two red lines are used for our energy calibration. You would move the prototype to let the electron hit the diffrent crystals all over. With present experimental setup, for each run, particles can cover more than 2 crystals. The center of x-y coordinate detector corresponds x and y fibre number 30 and electron energy 4 GeV(see plot 4).

During the experiment we roughly did energy calibration online by eye-checking ADC channel for different modules as zero order calibration. As a first step of offline energy calibration we did it with energy deposited in single module. Because the crystal size is the same for all the 36 crystals, the relationship between energy deposited in single module and real pariticle energy should be the same to all the crystals though the ratio of energy deposited in single module over real pariticle energy strongly depends on where the particles hit on the crystal and becomes maximum when the electrons hit the center of the crystal. Therefore, it is good to use the events which hit the center of crystal to do our energy calibration. As an example to show how well this calibartion works, in plot 5, the 422 run covers crystals numbered 9, 10 and 11 and 410 run 27, 28 and 29. It is clearly seen that these 6 crystals, though from different manufacture, have same maximum ratio.

In the first step we used the single module energy deposit which has resolution about 3.% (see plot 8) if the electrons hit the center of crystal. But if we use the sum of energy deposited in the crystal which the electrons hit and other 8 crystals

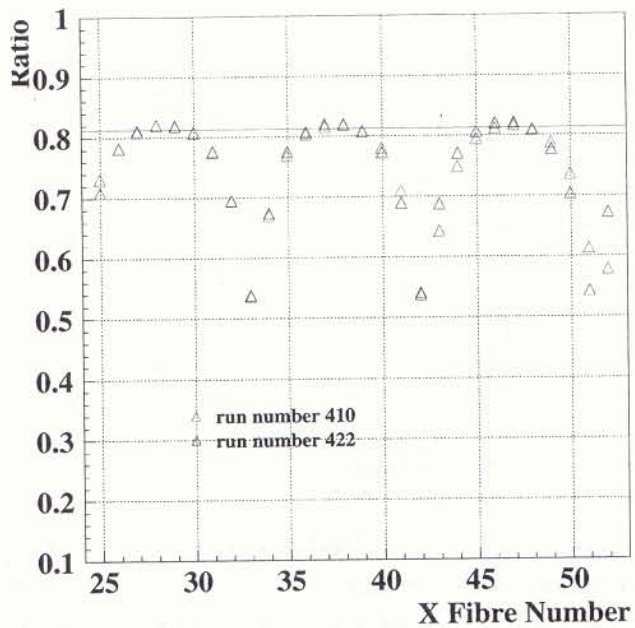

Figure 5: The ratio of energies deposit in single module over 3x3 modules.

around it(we call 3x3 energy), we can improve our calibration becaue in this case the 3×3 energy has resoultion about 1.6%.So, as a sencod step of our energy calibration, 3×3 energy is used. Following, the detailed calibration formalism will be reported.

The relationship between photomultiplier signal and energy deposited in the calorimeter (calibration constant) was obtained for each modul by studying a large sample of electron showers in the crystal array. We seek calibration constants for which each block has a signal which is proportional to the energy deposited, $E_{ij}=\alpha_j A_{ij}$, where α_j is the calibration constant for the jthe crystal,E_{ij} is the energy deposited in the jth crystal and A_{ij} is the signal from the jth crystal for the ith electron. The sum of all depsoited energy must equal to the incident energy

$$E_i = \sum_j^n \alpha_j A_{ij} \tag{1}$$

Multiplying eq. 1 by A_{ij} and summing over events yields eq. 2:

$$\sum_i E_i A_{ik} = \sum_j^n \alpha_j X_{jk} \tag{2}$$

where

$$X_{jk} = \sum_i A_{ij} A_{ik} \tag{3}$$

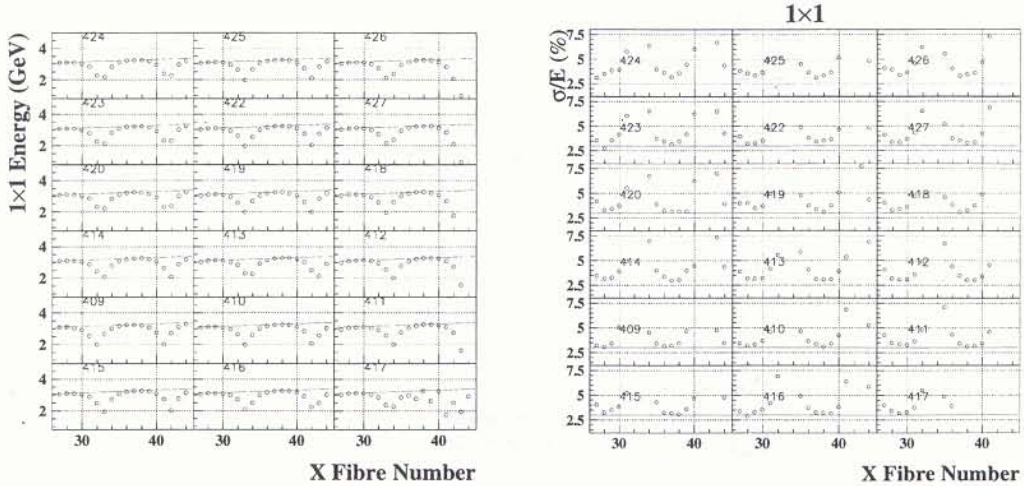

Figure 6: Left plot: Energy deposited in single module (The blue open circules are experimental results. The red line is the simulated energy); Right plot: Energy resolution corresponding the deposit energy shown in the left plot (the red line in the right plot is just for eye guiding)

Solving eq. 2 for the α_j yields a set of equations (eq. 4) whoes solution provides enough information to obtain the relative calibration constants with an overall normaliztion fixed by eq. 1 :

$$\alpha_l = \sum_k^n (\sum_i E_i A_{ik})(X_{kl})^{-1} \tag{4}$$

This solution is mathematically identical to that obtained by minimizing the energy resolution subject to the constant that the total energy equal the incident energy. In present case, as a second step, the n equals to 9 i.e. energy depsoited in 9 crystal. With this method, we only recalibrated the inner 16 crsytals with taking into account the energy leak to 20 edge crystals by using the calibartion constant we got in the first step.

3.2 Calibration Results

The calibartion results are shown in figures 6-8. Each figure consists of two plots: the left one is the deposit energy as a funtion of x fiber number and red line in it is the simulated energy; the right one is the energy resolution corresponds the desposit energy shown in the left plot and red line in it is to guide eyes. The reason to put them together is to show how the energy resolution depends on the deposit energy. To get all these figures, x fiber number changes from 26 to 35 and kept y fiber number being constant 30. Structure shown in plot 6 is understandable if you keep in mind that closer to center of crystal the particle hit, more energy

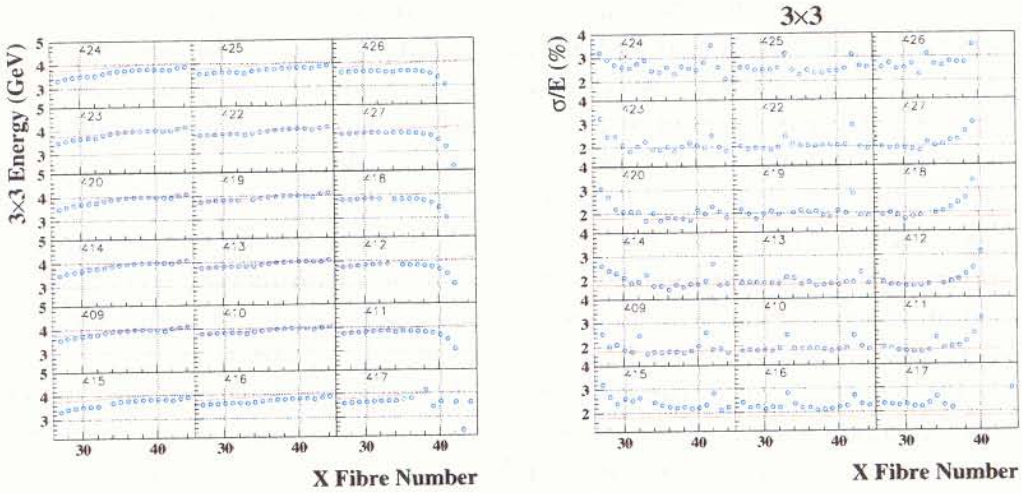

Figure 7: Left plot: Energy deposited in 3×3 module (The blue open circles are experimental results. The red line is the simulated energy); Right plot: Energy resolution corresponding the deposit energy shown in the left plot (the red line in the right plot is just for eye guiding)

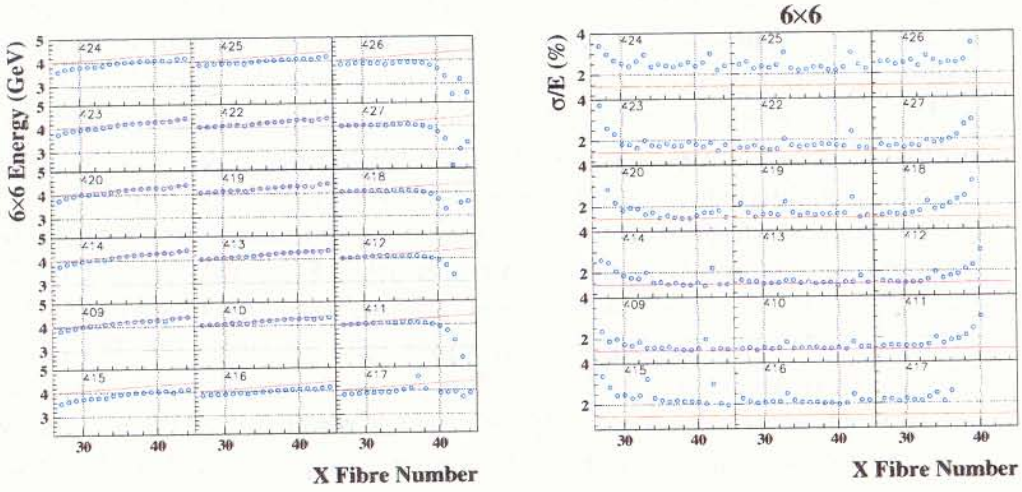

Figure 8: Left plot: Energy deposited in 6×6 module (The blue open circles are experimental results. The red line is the simulated energy); Right plot: Energy resolution corresponding the deposit energy shown in the left plot (the red line in the right plot is just for eye guiding)

deposited in this single crystal. And also, while more energy deposited in the single crystal, you get better energy resolution(Please see plot 7). Since we only used events which hit the center of crystal to do our calibration, you can only the see the biggest energy to match our simulated energy. The number in plot is run number. For each run, two crystals are covered, i.e. 424 run covers 1st and 2nd crystals, 425 run 3rd and 4th crystals and so on.... The crystal center is aroud 30 and 40 in unit of x fibre number. So from the plot, you can see that we have total 36 crystals are presented in this plot. X fibre number there just direct you where the paticle hit on the x-y coordinator detector and is used as a absolute refrence of prototype. Once you finished your movement of prototype, you can judge where the prototype is and which crystal is being studied. By studying the relationship between x fibre number and maximum energy deposited in the crystal, you can judge where is the center of crystal. Fox example, for run 424, we know that first 2 crystals were studied here and beacuse the maximum energy deposit are at 28 and 38 in unit of x fibre number you can tell they are the centers of these two crystals in the refrence of x-y coordinator detector and the distance between these two crystals is about 10 in unit of x fibre number which is about 20 mm and agrees well with the crystal cross section size. After each run, we moved the prototype so that incoming particles could hit the other crystals. For example, after we finished run 424, we moved the prototype left so that the particle could hit the crystals with number 3 and 4. That is why we have 16 runs for the energy calibration.

When particle hit one crystal, the particle energy is not only deposited in the crystal which the particle hit but also the energy could be deposited in other crystals by shower. To collect all the energy deposited in the prototype, you have to sum over all the energy possiblly deposited in the different crystals. Since the energy deposited in crystal far from the one which the particle hits could be as small as noise level. Therefore, how many crystals are needed to get the particle energy depends on how many crystals are needed to get best energy resolution.

Let us go further to see the results shown in figure 7 and 8. 3x3 energy in figure 7 means we got the depsoit energy by summing the energy deposited in the center one which the particle hit and other 8 crystals around it. When the electrons hit the 20 edge crsytals, there are less than 9 involved in the 3×3 energy calculation. So you can see from the plot that for them the 3x3 energy is less than the simulated energy. These effect are especially clear for crystals on fisrt and last coloum. Corrspondingly, we energy resolution getting worse when the electrons hit the edge crystals. The similar thing can be found in the figure 8 where the deposit energy were got by summing over energy depositet in all 36 crystals. Comparing the results shown in figures 6-8, it is clear that in figure 8 we got highest deposit energy and best energy resolution.

4 Energy Resolution

If the number of light photons is proportional to the energy of particles of phtotns absorbed in the prototype, the energy resolution should vary inversly as $\sqrt{E}$. However, some other sources can also impair the energy resolution such as the uniformity of cathode sensitvity, variation in energy conversion process in the prototype, incompletety of energy deposit in prototype and stability of prototype's temperature. All above affects work together with beam energy spread and electronic noise to give the energy resolution of the prototype. Therefore, before you get final energy resolution of the prototype, you have to carefully subtract the energy spread of the electrons which hit your prototype and energy spread caused by the electronic noise as well.

4.1 Beam Energy Spread

Beam energy spread comes from following sources: a) The beam profile before dipole could influce the energy spread of particle bombarding the prototype because particles with differnt energy and entry piont to the diople could reach the same point after dipole; b) In our energy resolution study, we assumed that the paritcles hit the same the x fibre have the same the energy. In fact, our x fibre is about 2.2mm wide in the energy spread dimension. So fibre width can cause the particle energy spread. c) Energy loss stragging can cause the energy spread before it reaches crystals. Before the particles reach the crystals, they have to pass through the sintillater, 5 meter air, x-y coordinate detector and other materials (for example 1 cm thick Aluminum) directly in front of crystals to close crystals inside the box. Particle energy spread just before our prototype was got from simulation with Geant3. The simulated energy spread for 4GeV is shown on the figure 25 and it's $\delta E/$E is 0.77%.

4.2 Noise Level

To get better energy resolution, you have to minimize the your noise leve for each channel. The noise level can be measured from the pedestal measurement. Assuming the widht of our pedestal without noise is aroud 1 or two channels, then, the widen width of the pedestal is from the electronics noise. The width of pedestal for each channel is shown in figure 26. If we take about the noise in energy unit, the noise level for different channel is ranged from 2 to 4MeV which totally can give maximum energy spread 0.4% which depends on how many channels involved in the energy calculation.

4.3 Energy resolution of the prototype

After subtracted the energy spread from the noise and beam line, the energy resultion is shown in figure 12 as a function of x-fibre numeber, i.e., as fuction of

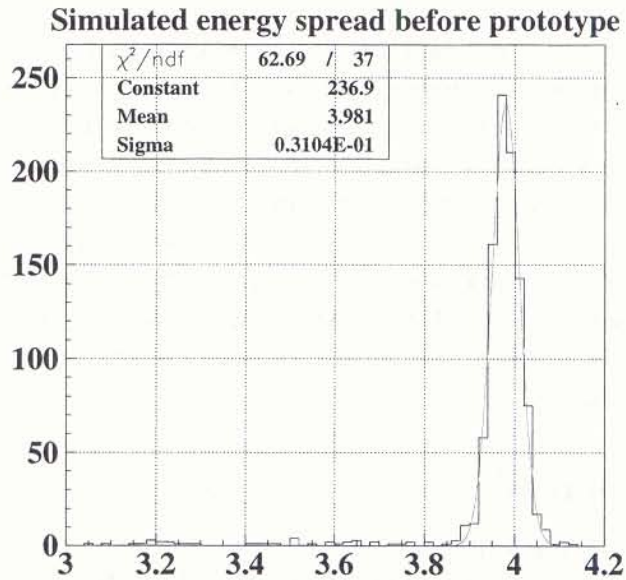

Figure 9: The energy spread before prototype

electron energy and position on which the particle hit. To compare with the data from literature, we employee the energy resolution got for crystal 21 and 22 because we got the best energy resolution on them. Since the energy resolution depends on the where the particle hits, we used here the average of energy resolutions, corresponding the centre fibre and two closest neigbor fibers on either side of the center one, to compare with the data from other authors. The centre fibre means here the one whcih corresponds the center of crystal. For the crystal 21 and 22, the centre fibre numbers are 29 and 38, and neigbors are 28, 30 and 37,39 respectively. The energy resoultion corresponding to these six fibers are shown in Table 1. The error for the energy resolution wiht any subtraction such as energy spread of particle and noise is statistical error.Error for the energy resolution after subtraction of energy spread of particle and noise is from both statistical error and error of determination of particle energy spread. The average energy resolution for crystal 21 and 22 are compared with the best energy resolution found in the literature(see figure 13). The expermental curve line shown there was got with less than 1GeV photon beam. Size of the crystals which were used to build up their prototype is the same as ours. From the figure 13 you can see that present experimental results are siting right on the cure go in[] though this curve got by fitting experimental data of less 1 GeV photon.

Table 1: energy resolution of center of crystal 21 and 22

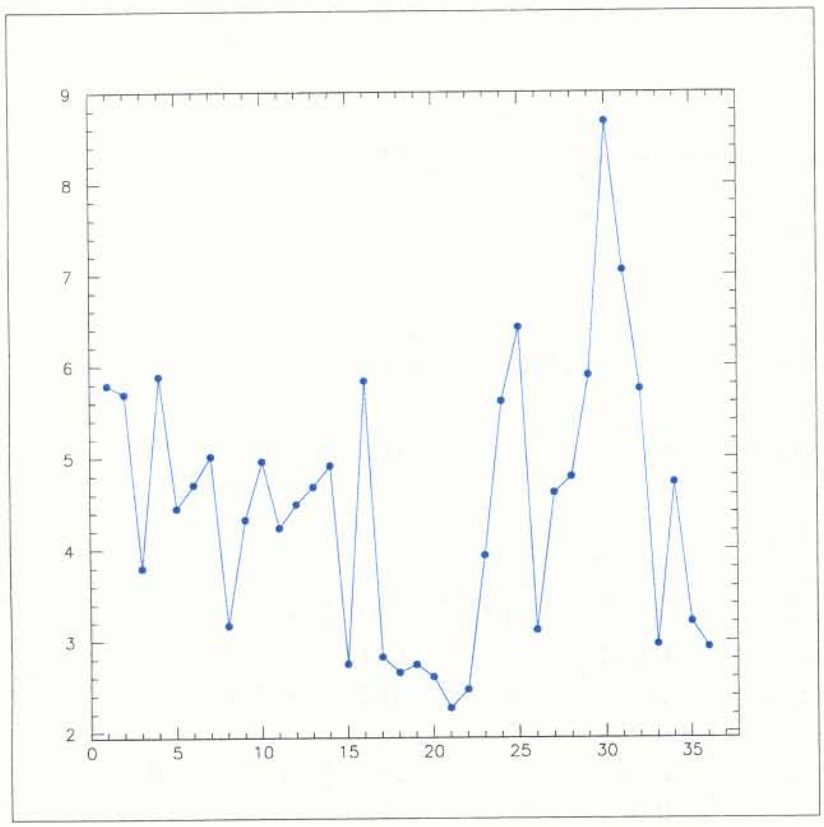

Figure 10: sigma of pedetal for different channels

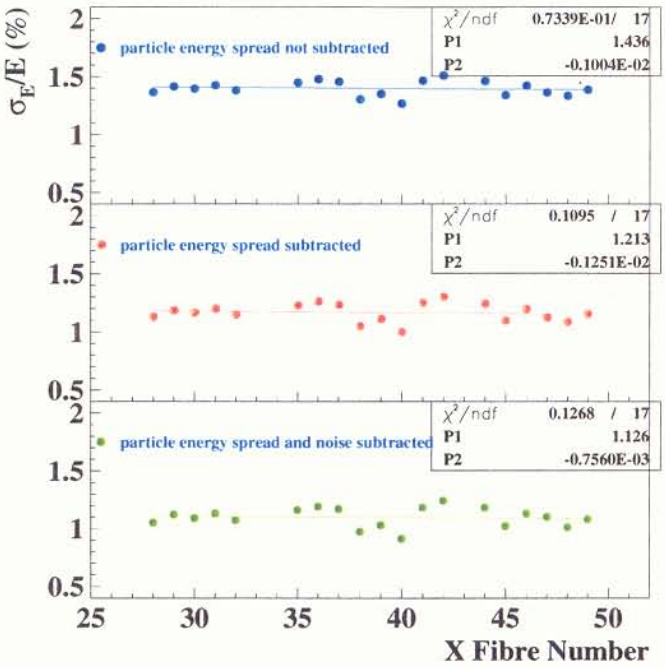

Figure 11: resolution of energy deposited in 36 crystals

Crystal number	21			22		
fiber number	28	29	30	37	38	39
energy resolution before subtracton(%)	1.365 ±0.043	1.413 ±0.045	1.394 ±0.042	1.454 ±0.043	1.302 ±0.049	1.350 ±0.038
after subtracton energy spread(%)	1.127 ±0.059	1.185 ±0.060	1.162 ±0.058	1.233 ±0.059	1.048 ±0.063	1.109 ±0.055
after subtracton noise(%)	1.05 ±0.059	1.12 ±0.060	1.09 ±0.058	1.17 ±0.059	0.97 ±0.063	1.03 ±0.055
Average electron energy (GeV)	3.979			4.165		
Average energy resolution(%)	1.09 ±0.06			1.06 ±0.06		

5 Position Resolution

5.1 Incident position reconstructon

The most obvious method to use to estimate the coordinate of the incident particle is to simply to calculate the center of gravity of the shower[]

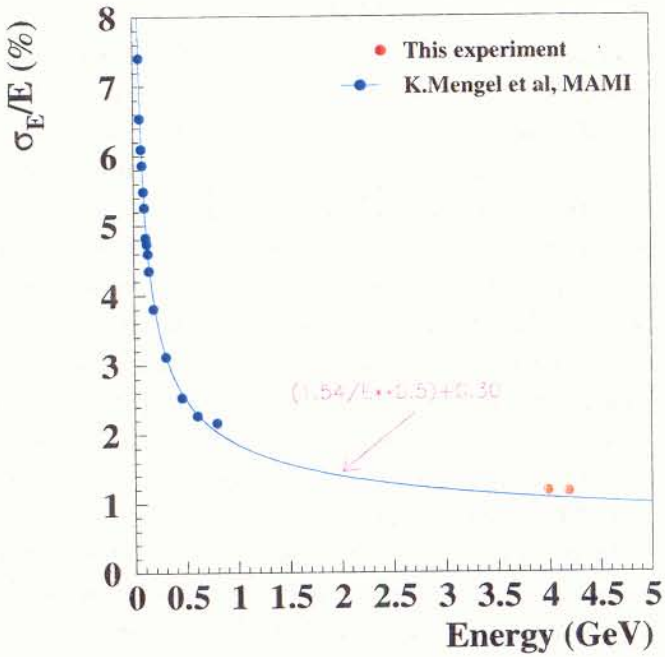

Figure 12: resolution of energy deposited in 36 crystals

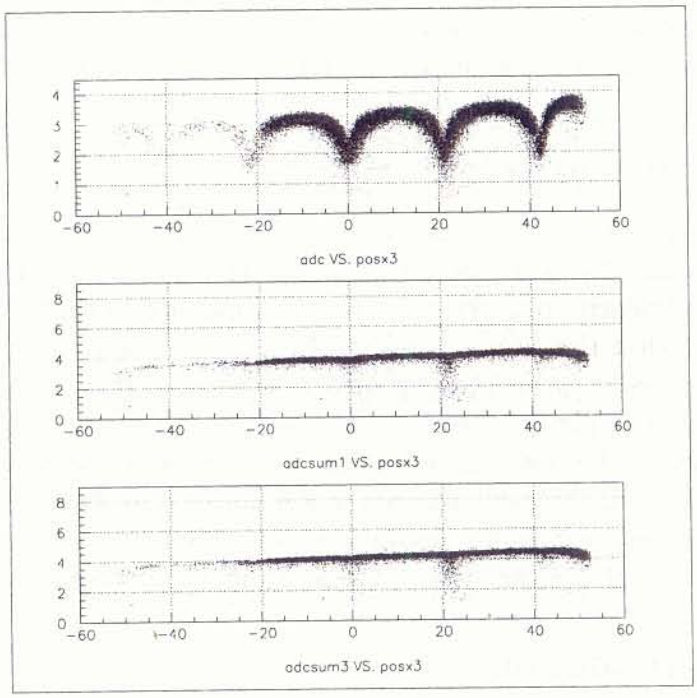

Figure 13: resolution of energy deposited in 36 crystals

$$X_{cal} = \frac{\sum_i^N w_i(E_i)x_i}{\sum_i^N w_i(E_i)} \tag{5}$$

where the x_i is the x coordinate of the center of module i and the weight factors w_i are taken as the energy E_i deposited in the that module. Equivalently, the weights may be viewed as the fration of the total shower energy in module i, $w_i = E_i/E_T$ with E_T=$\sum_i E_i$. Application of eq.(5) with such linear energy weights gives results as shown in figure 14 for 4 geV eletrons in the 3x3 $PbWO_4$ array. it is seen that although the individule fluctuations in the calculated position are quite small for a given position of incidence, there are large systematic errors in the calculated position relative to the catual incident position. It has been pointed out that the size of the deviation of the calculated position from the incident position depends on the ratio of the module cell size relative to the shower size. This is easily understood to arise from the fact that the radial energy falloff of the showers is exponential, and thus the energy deposited in the module decreases exponentially as a function of the distance from the point of the incidence. Therefore, if the module size is large compared to the shower size, then usually only a single module will contain most of the energy and so it will dominate the position calculation when its energy is weighted linearly. For this reason, algorithmis have been proposed which take into account the exponetial fallof of the shower profile by weighting the energy observed in the module logathimically. in general, it is found that use of the logarithmic weighting of the deposited energy signals produeces the best results[]. Rather than fitting the shower distribution, it is proposed to use eq.(5), but instead of weights which are linear in the energy deposited in a module, the weights to be used are given by the following expression:

$$w_i = max\{0, [W_0 + ln(\frac{E_i}{E_T})]\} \tag{6}$$

where once again E_i is the energy deposited the module i, E_T is the total energy of the shower and W_0 is a free parameter. This gives risse to weight factors which then vary linearly from the point on the incidence so that eq.(5) will then be valid. The fact that the energy observed in a module is actually a more complicated function, since it is an integral over a volume of the radial shower profile, hardly matters. For some reason, we got better energy resolution with 3x3 array. The dependce of the position resolution on the weight parameter W_0 is studied in []. In present work the same process was followed and finally we found that with W_0=0.47, the best coordinate resolution was achied. It is observed that the calculated position correlates very well with the incident position(see fig. 14).

5.2 Coordinate resolution

When you fix the x-y fiber number, you are fixing the incident position of incoming electron. By changing the x fiber number, you are chaning electron incident

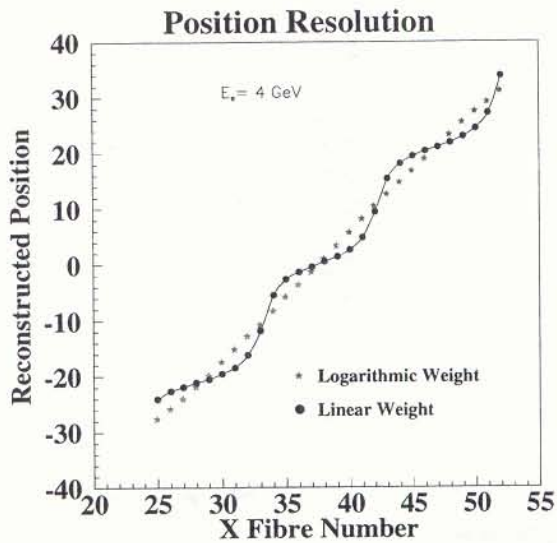

Figure 14: Reconstrued position as a function of the incident position x-fiber number

position and energy. The figure 15 just shows how the coordinate resolution depends on the incident position and energy. In general, position resolution depends on where the particle hits: in the center of crystal or the ont he edge of crystal. When the electrons hit the center of crystal, most the eletron energy is deposited in the single module and therefore the coordinate resolution is the worst. As the electrons hit further from the center of the crystal, the coordinate resolution is getting better. And you have the best coordinate resolution when the electrons hit the edge of crystal. Again as the incident position is moved as away from edge of the crystal toward the center of next crystal, the coordinate resolution will become worse again. The incident position dependence can be clearly seen from the left plot of figure 15. Again the x fiber here means electron incident position. For which fiber marks the center of the corresponding crystal, please review the left plot of figure 6. The right plot of figure 15 generally shows how well the reconstructed position correlates with incident position. For better view, please look at the figure 16. When you fix x-y fiber number, you fix the incident position of electron. So width of the fiber will impair the coordinate resoltion. You have to subtract the fiber width from the experimental coordinate resolution to get the actual the coornate resolution which is shown here in figure 17. From figure 17, it is clear that the coordinate resolution depends on the x fibre number as following:

$$\sigma_x = 1.62 + 0.35 * sin[(x - 26.6) * 0.69] - 5E - 3 * (x - 26.6) \quad (7)$$

Where σ_x is the sigma of reconstrcuted position and x is the fiber number. The

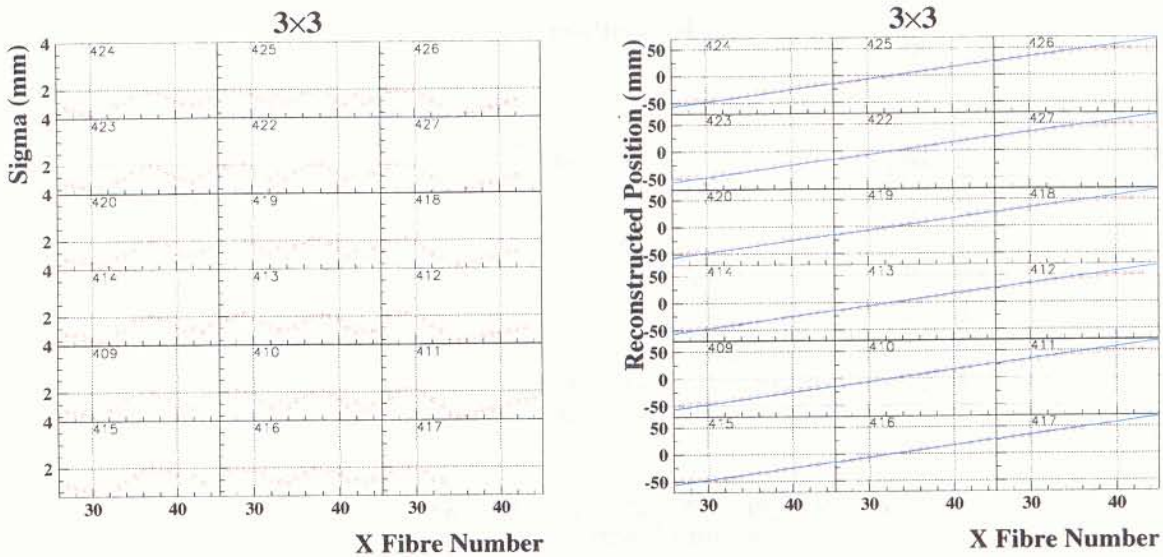

Figure 15: resolution of energy deposited in 36 crystals

number 0.69 can be subtracted if you remember that crystal size is about 9 fibers big and $2\pi/9$=0.695 which is very close to 0.69. The third part of this equation just tell us that with increasing the electron energy, the coordinate resolution will become better. For the energy region here is very small, we cannot get very accurate the energy dependence.

6 Rate dependence

All crsytal scintillators suffer fron radiation damage. To study this, we irradiated the crystals with different beam intensity to understand how the gain of the chosen channel changes. With increasing of the beam intensity the rates in the chosen channel will increase and so the gain of the channel will change(see figure 18). The gain change can be caused by two facts: 1) The gain change of phtottube; 2) The radiation damage in the crystal. Now the question is how much the gain change shown in figure 18 comes from the phototube and how much from the radiation damage in the crystals. With this question, we studied the gain rate dependence offline with LED.

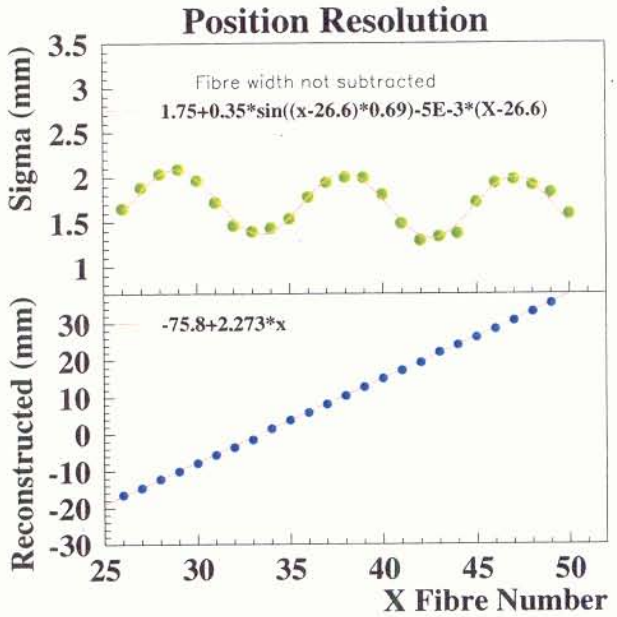

Figure 16: Reconstrued position as a function of the incident position x-fiber number

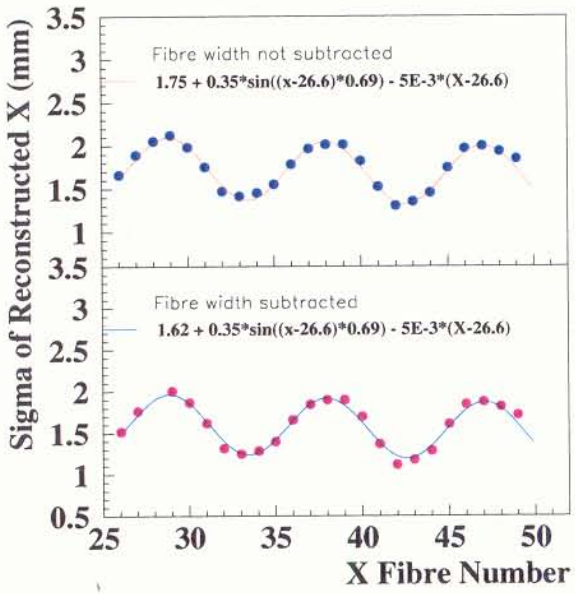

Figure 17: Reconstrued position as a function of the incident position x-fiber number

References