Expected Performance of Tile-Fiber Calorimeter for JLC

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Abstract
Extensive R&Ds of a CDF-type tile-fiber calorimeter with hardware-compensation are going on as a primary candidate for a calorimeter of the JLC detector. Required performance from physics, design criteria, and performance of test modules are reported. Results of shower shape analysis and photo-detector R&Ds are also reported briefly.

1 JLC Detector Overview

Basic concept of the JLC detctor is a large-volume medium-field general purpose detector. A cut-view of the detector is shown in Fig. 1. In order to achieve very good momentum resolution, the central tracker is designed to have large outer radius of 2.3m. Whole of the calorimeter system, though it also has large inner and outer radii of 2.5m and 4.0m, respectively, is designed to be located inside a large superconducting solenoid to achieve the best performance. This large radius is the key parameter of the JLC detector.

2 Design Concept

An important design criterium which has the most effect on the calorimeter system is that the detector be capable of achieving two-jet mass resolution better than the natural width of the weak bosons. This is quite important to do precision study of weak couplings as well as to discover/study Higgs boson which mass could be quite close to Z boson. Simulation study indecates that a calorimeter system of following energy resolutions with reasonable granularity can achieve two-jet mass resolution of about 1.3GeV as shown in Fig. 2.

$\sigma_E/E = 15\%/\sqrt{E} \oplus 1\%$ for EM shower

$\sigma_E/E = 40\%/\sqrt{E} \oplus 2\%$ for Hadron shower

In order to achieve such excellent hadron energy resolution, compensation is indispensable ; either hardware compensation or software compensation. We adopted hardware compensation because software compensation costs much higher due to its very fine granularity. For EM calorimeter, on the other hand, software compensation could also be a good choice because it needs fine granularity anyway.

As a structural option, we selected a CDF-style tile-fiber design. This design has very nice feartures as listed in Table 1.

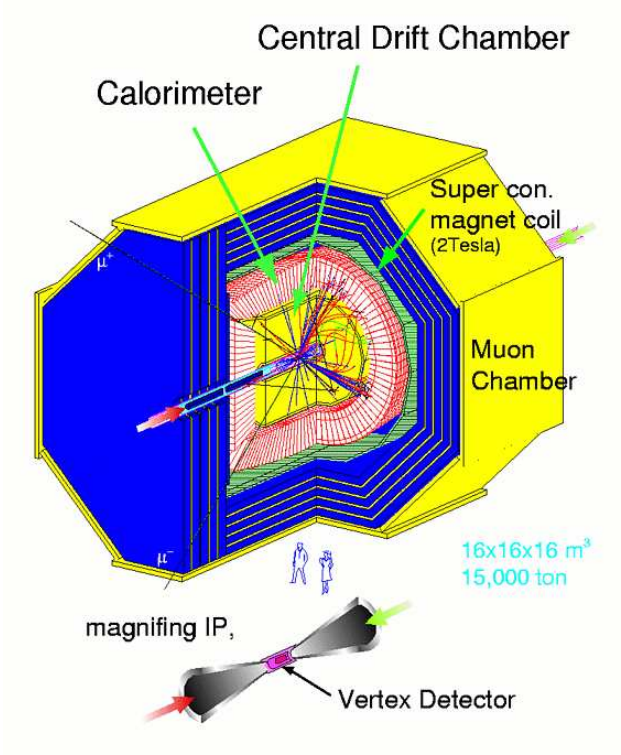

Figure 1: Cut-view of the JLC detector with an event overlapped.

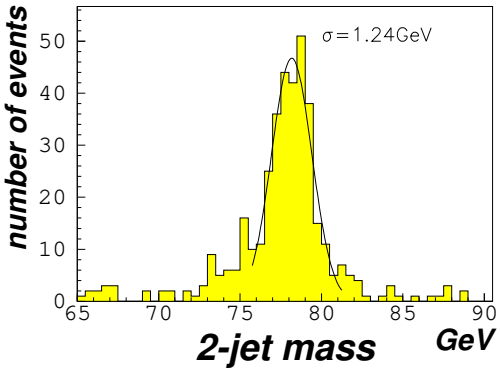

Figure 2: Two-jet mass resolution obtained with a quick simulator for the JLC detector. Generated mass and width are 80GeV and 0GeV, respectively.

Table 1: Characteristic feature of CDF-type tile-fiber calorimeters.

Merit	Demerit
Crack-free hermetic structure	
Very fine longitudinal segmentation	Reasonable transverse segmentation
Excellent hadron energy resolution	So-so EM energy resolution
Tower/projection structure naturally	Tile plane in Z-directioon
Inexpensive (< shashlik < liq.Ar < crystal < W-Si)	Low light yield

Low cost is one of the most important merit of the tile-fiber design especially for large-scale detectors. The fration of the cost proportional to the design parameters are as follows.

a) volume/mass 21%
b) transverse segmentation 79%
c) longitudinal segmentaion 7%

Therefore large volume or fine longitudinal segmentation can easily be realized with the tile-fiber design, while fine transverse segmentaion costs significantly. For example, reducing transverse segmentation size of EM calorimeter only to 2/3 would increase the total cost by 40% unless new clever scheme would be invented to make tiles or fiber assemblies.

For the tile-fiber design, there were two important features left unknown ;

- Feasibility of thin tiles were unknown. In most cases, 4mm-thick scintillator tiles had been used so far. In order to achieve hardware compensation with design energy resolution, EM calorimeters should be made with 1mm-thick scintillator tiles. Feasibility of such thin tiles should have been investigated.
- Possibility of compensation was unknown. Simple lead/scintillator sandwich was known to achive compensation by ZEUS group [1]. The CDF-type tile-fiber structure, however, has additional plastic plates stuck on the scintillator plates in order to accomodate optical fibers. The effect of these plastic plates on compensation must have been studied.

These issues have also been studied extensively , but are not reported here.

3 Performance Study

Study of two-jet mass resolution has been performed in detail with a quick simulator in order to identify which performance is the most important to achieve the required mass resolution. Fig. 3 shows contribution of each analysis component to the two-jet mass resolution for the simplest reaction

$e^+e^- \to ZH, Z \to \nu\bar{\nu}$ at $E_{CM} = 400GeV$

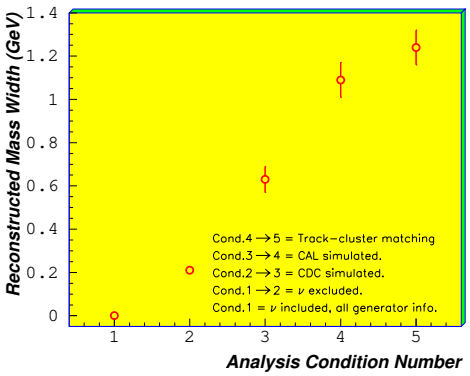

Figure 3: Decomposition of two-jet mass resolution for the process $e^+e^- \to ZH, Z \to \nu\bar{\nu}$ at $E_{CM} = 400GeV$. Horizontal axis indicates analysis conditions. At each analysis step, generator information is replaced with simulated result one by one.

The plot shows how the reconstructed mass width increases each time generator information is replaced with simulated results. The result shows contribution of each step as follows.

CDC momentum resolution	$\sim$ 0.6GeV
CAL energy resolution	$\sim$ 1.0GeV
Cluster-Track matching	$\sim$ 0.6GeV
Total Width	$\sim$ 1.3GeV

Preliminary study with not-optimized analysis parameters for reaction

$e^+e^- \to W^+W^-$ at $E_{CM} = 400GeV$

gave two-jet mass resolution for W of $\sim$ 3.3GeV including its natural width. This width was decomposed as

Natural width of W	$\sim$ 1.6GeV (in terms of σ)
Neutrino escape	$\sim$ 0.8GeV
CDC momentum resolution	$\sim$ 1.3GeV
CAL energy resolution	$\sim$ 1.2GeV
Cluster-track matching	$\sim$ 1.9GeV
Jet clustering	$\sim$ 1.1GeV
Total Width	$\sim$ 3.3GeV

It is seen that topological analysis, jet clustering and cluster-track matching, is important for such events. Improvement of algorithm is needed to improve mass resolution, as well as study and optimization of detector parameters.

Table 2: Parameters of test module configurations.

	Hanging-File Module	Tile-Fiber Section
Transverse Size	1m × 1m	1m × 1m
Thickness	6 λ total	4 λ
Scintillator Thickness	2mm	2mm
Lead Thickness	4mm-16mm, step 2mm	8mm
Transverse Segmentation	none	5 × 5
Longitudinal Segmentation	42 at maximum	4

4 Test Module Performance Study

In order to establish that a tile-fiber calorimeter with hardware compensation can achieve the required performance, a hanging-file hadron calorimeter test module was constructed. What to be established were as follows.

- e/π ratio and hardware compensation
- Energy resolution
- Linearity
- Tower-boundary response

A series of low-energy beam test was done at KEK in order to measure the stochastic term of energy resolution and e/π ratio with the best accuracy, while a high-energy beam test is scheduled at FNAL this summer to measure the constant term of energy resolution and linearity precisely. It should be noted that e/π ratio, an important parameter of calorimeters to predict resolution, linearity, and non-Gaussian behaviour, is best determined at low energy since it approaches to 1 at high energy regardless calorimeter structures.

The low-energy beam test at KEK was done in two steps.

First, a reconfigurable hanging-file module similar to the SDC test module [2] was made. This module had no transverse segmentation but had very fine longitudinal segmentation. This module was used to establish hardware compensation and to study basic characteristics of hadron shower itself.

Afterwards, the 1st 4λ of the hanging-file module was modified to a tile-fiber structure based on the results of the beam tests of the hanging-file module. This tile-fiber section has 5×5 tower structure and four longitudinal segmentations. The rear part remained unchanged.

Important parameters of the modules are listed in Table 2 for both design.

Energy resolution for pions measured with the hanging-file module is shown in Fig. 4 [3]. Energy resolutions of $\sigma_E/E = 15.2\%/\sqrt{E} \oplus 0.0\%$ for electrons and $\sigma_E/E = 39.6\%/\sqrt{E} \oplus 1.0\%$ for pions were achieved for lead thickness of 4mm and 8mm, respectively. Here the constant terms have almost no significance. We further achieved $\sigma_E/E = 33.6\%/\sqrt{E} \oplus 0.0\%$ for pions with 4mm-thick lead plates, which is one of the best results achieved so far. e/π ratio was also measured for various

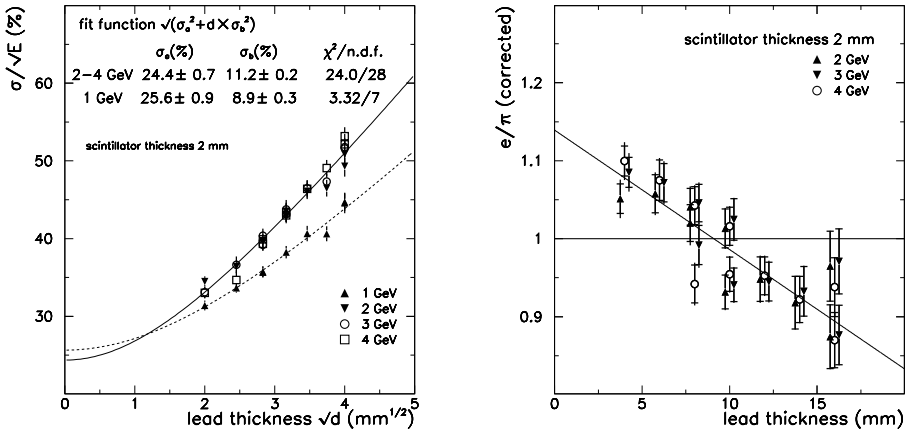

Figure 4: Energy resolution (left) and e/π ratio (right) for pions as a function of lead thickness. Horizontal axis is a $\sqrt{leadthickness}$ for the left figure.

lead thickness as shown in Fig. 4. It is seen that the hardware compensation was achieved for lead thickness of 9.1mm in the case of 2mm-thick plastic scintillator.

In the case of the tile-fiber design, a plastic plate is stuck on each scintillator plane in order to accomodate optical fibers running from tiles to photo-detectors. This plate would affect resolutions or hardware compensation. This effect was also studied using this hanging-file module. It was shown that acryl plates slightly worsened energy resolutions, while e/π ratio did not change when acryl plates were positioned downstream-side of the scintillator planes. Based on these results, design of the tile-fiber module was determined.

Fig 5 shows cross-talk between towers for the tile-fiber test module. It shows relative energy deposit to each tower when electron was injected to the central tower. This cross-talk is consistent to light cross-talk measured at a bench test with an RI source. Fig 6 shows boundary response of the tile-fiber module for pions (upper) and for electrons (lower). Left figure is energy measurement, and right figure is energy resolution. No anomaly was observed at tower boundaries for pion responses. On the other hand, significant enhancement was observed for electron energy measurement. This anomaly is bigger than those observed at CDF endplug calorimeters due to thinness of scintillator tiles. Special care should thus be taken when making EM modules with thin tiles.

5 Shower Profile Analysis

The hanging-file test module had very fine longitudinal segmentation ; 42 sampling over 6λ at the maximum. This enebles detailed analysis of longitudinal shower profile. Similar analysis was done by H.Miyata [4] for EM showers for CDF calorimeters. This information is quite useful for

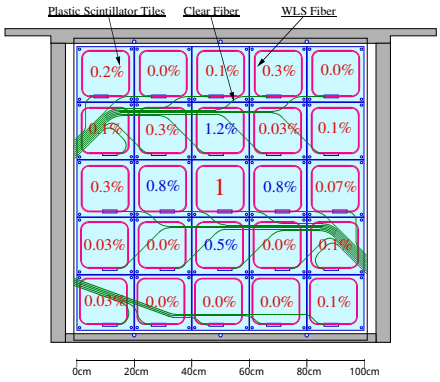

Figure 5: Cross talk between towers when electron was injected at the center of the central tower. Curves in the figure indicate route of optical fibers.

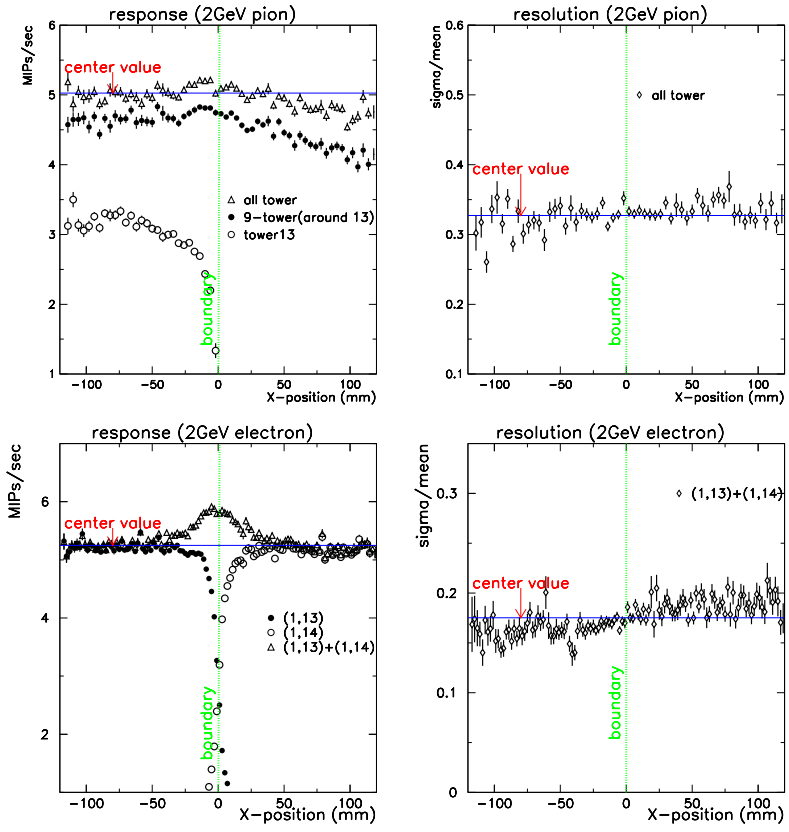

Figure 6: Measured energy (left) and energy resolution (right) for pions (upper) and for electrons (lower) at the tower boundary. Open triangles in the left figure are total energy.

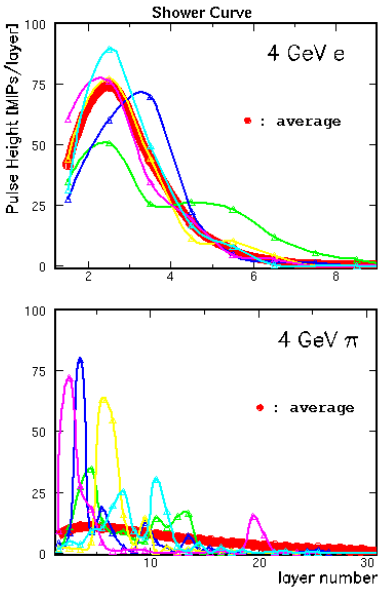

Figure 7: Average and event-by-event shower shapes for electrons and for pions.

- e/π identification,
- optimization of number and depth of longitudinal segmentation, and
- input to quick simulators as shower generator with realistic fluctuation.

Fig. 7 shows average and event-by-event shower shapes for electrons and for pions measured with the hanging-file module. In the case of the EM showers, event-by-event shower shape is similar to the average shape, while in the case of the pion shower, event-by-event shower shape fluctuates a lot apart from the average shape. This large fluctuation can be parameterized by expanding event-by-event shower shape using a set of orthogonalized fluctuation eigen vectors and their expansion coefficients.

Not only this analysis is useful to improve e/π separation, this is also useful to optimize longitudinal segmentation of calorimeters. For example, the 1st eigen vector was measured to have one single node at 25Xo. In order to do e/π separation with only E_{EM}/E_{hadron} information, optimum thickness of EM calorimeter is thus concluded to be 25Xo. Analysis of higher-mode eigen vectors will tell you how many segmentation at which depth will be the optimum segmentaion to achieve required e/π separation performance.

Another important fruit of this analysis is a shower generator. Realistic hadron shower with realistic fluctuation can be generated by overlapping fluctuation eigen vectors with weights generated according to the expansion coefficient distribution. This can be a fast and realistic hadron shower terminator for quick simulators.

These analyses is yet in progress.

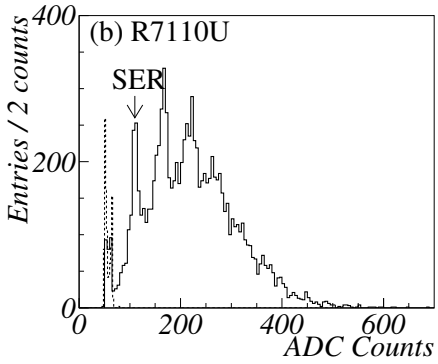

Figure 8: Output spectra of HAPD at very low photon intensity.

6 Photon Detector R&Ds

Sampling calorimeters with hardware compensation result in low photon yield due to its low sampling fraction. For the JLC detector case, whole the calorimeter is designed to be located in solenoid magnetic field. Therefore photon detectors with high gain, high sensitivity operational in strong magnetic field is needed.

Recently hybrid devices such as hybrid photo-diodes, hybrid APDs, or hybrid CCDs have been making quite rapid progress. Our group has also been studying applicability of such devices since 1993. Based on the study, we presently aims at using HAPD for preshower destectors, HCCD for shower-max detectors, and high-gain HPD for EM and hadron calorimeters.

Fig 8 shows one of our test results of an HAPD, HPK R7110 [5]. It clearly shows a single-photon peak, which is mandatory feature for preshower detectors. At present, the size of APD is limited to several milimeters. It is needed to develop large-area, multi-pixel APDs to built in the HAPDs. Another problem now is S/N ratio in noisy environment. Further R&D is thus necessary aiming at, for example, integration of readout preamps on devide.

HCCD is a super multi-channel detector in its nature, and thus is very suitable to read out fiber bundles from shower-max detectors. Recently RD46 collaboration succeeded to obtain nice single-photon peak [6]. Though a pixel of HCCD does not have very wide dynamic range, photons from fibers distributes tens of pixels. Therfore cluster charge measurement can have sufficient dynamic range for e/π identification and cluster centroid determination. In order to use it in JLC experiment, however, R&D for high-speed readout is necessary.

Compared to the HAPD and HCCD which need more R&Ds, high-gain HPD is more or less matured device. The cost is still too high, but would be reduced as a result of mass production in the construction phase.

7 Summary

Requirement on the JLC calorimeter from the physics capability was studied. Based on the study, calorimeter design was done. A hanging-file type and a CDF-type tile-fiber calorimeter test modules were made, and a series of beam tests were done at low energy. We achieved following energy resolutions ;

$\sigma_E/E = 15.2\%/\sqrt{E} \oplus 0.0\%$ for EM shower

$\sigma_E/E = 39.6\%/\sqrt{E} \oplus 1.0\%$ for pion shower

This satisfies requirement from the physics capability. The test module also showed nice tower boundary response for pions.

Photo-detector R&Ds are also going on, aiming at using HAPD and HCCD for preshower and shower-max detectors, respectively.

References

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