A Novel Strip-Energy splitting Algorithm for the Fine Granular Readout of a Scintillator Strip Electromagnetic Calorimeter

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Abstract

We describe an algorithm which has been developed to extract fine granularity information from an electromagnetic calorimeter with strip-based readout. Such a calorimeter, based on scintillator strips, is being developed to apply particle flow reconstruction to future experiments in high energy physics. Tests of this algorithm in full detector simulations, using strips of size $45 \times 5 \text{ mm}^2$ show that the performance is close to that of a calorimeter with true $5 \times 5 \text{ mm}^2$ read-out granularity: for example, jet energy resolution $\sigma_E/E = 3\%$ at 100 GeV. The performance can be further improved by the use of $10 \times 10 \text{ mm}^2$ tile-shaped layers interspersed between strip layers.

1 Introduction

In the experiments being designed for next generation electron-positron colliders, the particle flow approach (PFA)\cite{1, 2} is the leading candidate to achieve the excellent jet energy resolution required to fully exploit the possibilities afforded by the colliders’ well-defined initial and clean final states. In PFA, the energy of charged particles is measured by the tracking system, which has a much better momentum resolution than the energy resolution of calorimeters: factor 10 for 100 GeV single pion, $10^2$ for 10 GeV single pion comparing with a Hadron calorimeter (HCAL). The calorimeters are used to estimate the energy only of neutral particles. In order to apply this approach, the calorimetric showers of each particle must be individually reconstructed. The granularity of calorimeter readout is therefore a key issue.

As an example, the sampling electromagnetic calorimeter (ECAL) being designed for the International Large Detector (ILD, a detector being designed for use at the International Linear
Collider (ILC) [3]) is optimized to have a lateral segmentation of $5 \times 5\,\text{mm}^2$ and 20 - 30 longitudinal samplings in $23\,\text{X}_0$, for the best performance in a finite cost giving a total of $\sim 10^8$ readout channels. One technology being developed to achieve this high calorimeter granularity is based on plastic scintillator strips individually read out by miniature photon detectors, for example pixelated photon detectors (PPD; SiPM is also frequently used.) [4].

The use of long scintillator strips rather than tiles of size $5 \times 5\,\text{mm}^2$ makes the design of such an ECAL more feasible, and reduces its cost, due to the reduced number of readout channels. Successive ECAL layers have orthogonally aligned strips, giving an effective granularity close to the strip width. The CALICE collaboration has developed and constructed ECAL prototypes based on this technology, using scintillator strips of length 45 mm and width 5 or 10 mm, individually read out by PPDs [5, 6].

This paper presents a reconstruction method which can be used to extract close to $5 \times 5\,\text{mm}^2$ effective granularity from such long scintillator strips, and reports on measurements of its performance using events fully simulated in ILD. Details of this detector are given in the next section, the reconstruction procedure is explained in section 3, and section 4 describes the calibration procedure. The position resolution achieved by this method is reported in section 5. Particle separation abilities are reported on and discussed in section 6, and the achieved jet energy resolution in two-jet events is reported and discussed in section 7. Finally we discuss the results in section 8 and summarize this study in section ??.

2 Detector model

Starting from the interaction point, the ILD consists of a vertex detector, silicon tracking layers, a large time projection chamber (TPC) surrounded by additional silicon tracking detectors, a calorimeter system consisting of electromagnetic and hadronic sections, all placed within a solenoidal magnetic field of strength 3.5 T. The steel return yoke is instrumented to provide muon identification. The basic structure consists of a central, “barrel”, region aligned with the beam axis, closed by two “endcaps” in the forward regions. The ECAL barrel detector has an octagonal cross-section, a length of around 5 m, and an inner radius of 1.85 m. A cylindrical coordinate system with its axis (z) aligned with the beam line is used in this paper. More details of the ILD design can be found in [3]. The ILD is simulated in MOKKA [7], a Geant4-based simulation tool [8]. Figure 1 left shows a multiple-jet event simulated in ILD.

The ILD strip-scintillator ECAL (strip-ScECAL) is a sampling calorimeter. In the simulation model used in this study, thirty sensitive layers are interleaved with tungsten plates of thickness 2.1 (4.2) mm in the inner twenty (outer nine) layers. These tungsten absorber layers lead totally 22 $\text{X}_0$, and 0.8 mm readout circuit boards, copper radiator plates, and sensor layers contribute less than 1 $\text{X}_0$. The sensitive layers are tiled with scintillator strips of thickness 1 mm. Strips are aligned orthogonally in successive layers. A dead volume of size $2.5 \times 1.0 \times 0.91\,\text{mm}^3$ is implemented at the edge of each scintillator to represent the volume occupied by the PPD. When we use shorter scintillator strips, the ratio of this dead volume to the strip increases. Since the shorter strip ECALs are tested as references toward the nominal strip length of 45 mm, the PPD thickness, 0.91 mm was scaled by the strip length in the case of strips shorter than 45 mm to keep comparisons be fare, while real PPD thickness cannot be easily changed. Each strip is enveloped by a reflective film of thickness 57 $\mu\text{m}$. Printed circuit boards housing the front end electronics and copper heat radiators are included in each layer. The total thickness of such an ECAL is around 200 mm.

Four different scintillator tile configurations were used in this study:

1. $5 \times 5\,\text{mm}^2$ tiles (“$5\times5$”);
2. $45 \times 5\,\text{mm}^2$ strips (“$45\times5$”);
3. alternating layers of $5 \times 5\,\text{mm}^2$ tiles and $45 \times 5\,\text{mm}^2$ strips (“alt5”); and
4. alternating layers of $10 \times 10\,\text{mm}^2$ tiles and $45 \times 5\,\text{mm}^2$ strips (“alt10”).
Successive strip layers were always orthogonally aligned. An based on forty layers of $30 \text{ mm} \times 30 \text{ mm} \times 3 \text{ mm}$ scintillator tiles interleaved with $20 \text{ mm}$ iron absorbers was simulated in this study.

### 3 Strip Splitting Algorithm

A simple algorithm, the Strip Splitting Algorithm (SSA), has been developed to extract fine granularity information from the long strip geometry. Each strip is split into $n$ virtual cells along its length; $n$ is chosen to result in approximately square virtual cells, as an example, a $45 \times 5 \text{ mm}^2$ strip is split into nine $5 \times 5 \text{ mm}^2$ cells. The total energy $E_{\text{strip}}$ detected by the strip is then distributed among the virtual cells according to the weights estimated by using the energy deposited on the strips in immediately neighboring layers, having an intersection with the strip being considered, when seen from the interaction point of ILD. Consequently, the energy deposited on the virtual cell $k$ is estimated as,

$$E_{\text{virtual}}^k = \frac{E_{\text{strip}}^{i_-, k} + E_{\text{strip}}^{i_+, k}}{\sum_i (E_{\text{strip}}^{i_-, i} + E_{\text{strip}}^{i_+, i})},$$

where $k$ is the index of the virtual cell within the strip, $i_-(i_+)$ is the index of neighboring intersecting strips in inner (outer) layer, and $E_{\text{strip}}^{i_\pm, k}$ is the energy deposited in the strip $i_\pm$ having an intersection in the range of virtual cell $k$. Figure 2 shows a schematic of the SSA procedure.

In the case of the alt10 model, the $10 \times 10 \text{ mm}^2$ tile is first split into $2 \times 2$ virtual cells. The neighboring strip layers are used to decide how to partition the tile’s energy among the virtual cells. These layers have orthogonal strip direction in deeper and shallower layers to each other across the tile layers. Therefore, a tile layer can be split into two lateral dimensions: a tile layer is split into $5 \times 5 \text{ mm}^2 \times 2 \text{ mm}^2$ virtual cells. In a second step, these virtual cells (originating from the $10 \times 10 \text{ mm}^2$ tiles) are used to decide the partitioning of the energy among the strips’ virtual cells. Although the use of $5 \times 5 \text{ mm}^2$ interleaving layers means that the presence of orthogonally aligned strip layers is no longer used, it is used again when tiles are larger than $5 \times 5 \text{ mm}^2$ in this way.
Events were analyzed using a particle flow reconstruction algorithm. In the results presented later in this paper, the PandoraPFA algorithm[1, 9] was used to analyze events, together with other standard ILD reconstruction programs (e.g. for tracking) in the MarlinReco[10] package. PandoraPFA uses as input the energy and position of calorimeter deposits. When SSA was used, the center of each virtual cell and its assigned energy were used; when no SSA was used, the central position and total energy of each strip were used.

PandoraPFA, MarlinReco, and Mokka were taken from the software package ILCSoft v01-16-02.

4 Calibration

The calorimeter was calibrated by studying the energy deposited by 10 GeV photons for the electromagnetic response, and 10 GeV neutral long lived Kaons ($K_L$) for the hadronic response. Particles were injected from the IP in a direction almost perpendicular to the beam-line (in order to avoid the central electrode of the TPC) and uniformly distributed in azimuth. The calibration factors used to convert between the energy deposited in the scintillator and that deposited in the whole calorimeter were chosen to give a mean energy, after PFA reconstruction, equal to the incident particle energy.

Hadronic showers can start in the ECAL, because the ScECAL has a nuclear interaction length of 0.8 $\lambda$, and electromagnetic showers can have tails in the HCAL. In those cases hadrons deposit the shower energy in the ECAL with a ratio different from the electromagnetic shower, and vice versa. Thus the correction factors $h/e$ are defined for the ECAL and the HCAL separately and optimized to give the best jet energy resolution [11].

The ECAL was re-calibrated for each ECAL configuration, while a single HCAL calibration was used for all configurations.

In order to determine the threshold on each hit on the ECAL and the HCAL, the deposited energy of 10 GeV anti-muons in cells were measured and its most probable value (MPV) were determined by fitting with gaussian convoluted landau function. For the ScEAL, 0.5 MPV was set as a threshold for a strip, while 0.3 MPV was set for the energy on the virtual cells, since
threshold cut were implemented before SSA. For the HCAL, 0.3 MPV is set according to the default value of standard analysis of the PandoraPFA.

5 Position of clusters

The precise reconstruction of cluster positions is important in a PFA analysis to ensure good matching between tracks and calorimeter clusters. In this study, 10 GeV photons were fired into the 45×5 ECAL from the IP, varying the ECAL injection position along the z direction. The injected position was taken to be the intersection on the ECAL front face of the line joining the reconstructed cluster position and the IP. Figure 3 shows the difference between the reconstructed and true photon injection positions, as a function of the injected position. The size of the vertical error bars reflects the width of the reconstructed position distribution.

When SSA is not used, a strong position-dependent bias of up to 5 mm is observed, corresponding to cases when the photon shower passes near the ends or center of a strip (z = 68 mm corresponds to the center of strips aligned with the z axis). When SSA is used, these biases are almost completely removed, and cluster positions are reconstructed to better than 1 mm. All injection positions are plus side in z with respect to the center of the virtual cells. This makes a small systematic shift within the statistical uncertainty even with SSA as shown in Fig. 3.

Figure 3: Shift of reconstructed position for 10 GeV photons. Vertical bars show only statistical uncertainties.

6 Two-particle separation

To investigate the separation ability of the strip-ScECAL with SSA, di-muon events and π⁰ decays for the photon-photon separation were studied. Those events were investigated rather to see the simplified phenomena to understand what happens in the calorimeter than the importance of physics case. Di-muon events show the simplified phenomenon of two calorimeter tracks close together making the “ghost”: two particles simultaneously incident in a square area with less than the strip length make one or two excess clusters. Two photons from the π⁰ decays are various samples of the pairs of electromagnetic clusters. The reconstructed invariant mass can provide good test of the separation and reconstruction ability.

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1 The position of a calorimetric cluster is defined as the energy-weighted mean position of its constituent hits.
6.1 $\mu - \mu$ separation

Di-muon events provide a sensitive system for measuring two-particle separation in different ScECAL designs. Two anti-muons of momentum 10 GeV were injected into the detector at almost normal incidence to the beam-line, changing injection positions with the same distances, 5.0 - 7.1 mm, in both azimuthal and polar angles. The resulting simulated events were analyzed using SSA and PandoraPFA.

Figure 4: Left: fraction of correctly reconstructed 4000 of di-muon events as a function of the distance between the muons at the front face of the ECAL. Right: energy deposit of two electrons incident simultaneously on 45×5 strip-ScECAL reconstructed with SSA. Two of four peaks are ghosts.

The use of interleaved tile layers removes the ambiguities leading to ghosts, and dramatically improves the situation, giving a performance comparable to that of a tile-based ScECAL.

6.2 $\pi^0$ reconstruction to study two-photon separation

A $\pi^0$ meson decays into two photons, which can be reconstructed using only calorimeter information. The $\pi^0$ energy has a strong influence on the opening angle between the two photons, and variations in the decay angle give rise to different photon energies in the laboratory frame. Samples of $\pi^0$ decays at different energies are therefore a powerful tool to measure the ECAL performance, both in terms of pattern recognition (the ability to identify two clusters), and energy resolution (by considering the invariant mass of identified clusters).
Figure 5 shows the fraction of $\pi^0$ events in which one, two, and more than two photons are reconstructed in the alt10 ScECAL. In each condition 4000 $\pi^0$s were injected from IP with the same manner as the particles for the calibration discussed in section 4. The number of events with no reconstructed photons is less than 0.5% for all $\pi^0$ energies. In around 9% of events, at least one of the photons from the $\pi^0$ decay converts before reaching the ECAL. All ScECAL geometries, including the 5×5 ScECAL, show similar behavior. This indicates that the increasing rate of $\pi^0$ mis-reconstruction with energy is due to both the merging of photons into a single cluster and the fragmentation of photon clusters.

![Figure 5](image)

Figure 5: The fraction of the number of events which, when reconstructed in the alt10 strip-ScECAL, contain one, two, and more than two reconstructed photons. The 8000 of $\pi^0$ samples were created for each data point. The statistical uncertainties are estimated but they are too small to see. The opening angle between the pair of photons decreases as the $\pi^0$ energy increases, and this then makes confusion or division of reconstructed clusters.

Figure 6 shows various characteristics of $\pi^0$ events in which exactly two photon-like clusters, trackless clusters in the ECAL were identified. Figure 6a (6b) shows the reconstructed invariant mass of such events at different $\pi^0$ energies in a 5×5 tile-ScECAL (45×5 strip-ScECAL with SSA). Figure 6c shows the fraction of $\pi^0$ events which have exactly two identified photon-like clusters with a reconstructed invariant mass greater than 0.1 GeV/$c^2$, for the four ScECAL geometries considered. The use of alternate tile layers improves the performance compared to a purely strip-based geometry, as was also seen in the case of di-muon events.

Figure 6d shows the means and standard deviations of Gaussian fits to the mass spectra for $\pi^0$ of different energies, reconstructed in different ScECAL geometries. SSA was used in all models except the 5×5 tile-ScECAL.

These studies show that some level of $\pi^0$ reconstruction is possible at energies of up to $\sim 30$ GeV. No large performance differences were seen between the four considered ECAL geometries.

7 Jet energy resolution

Reconstruction of two-jet events is an important benchmark test of the PFA. The $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s$) events at center-of-mass energies of 91.2, 200, 360, and 500 GeV were generated for successive studies in $10^4$ events for individual test conditions. These events were fully simulated in the ILD simulation described earlier, and reconstructed using MarlinReco, including SSA and PandoraPFA.
To evaluate the jet energy resolution, the “RMS90” measure is used: only events in the barrel region (absolute values of cosine of the angle between original quarks known from the simulation information and beam line < 0.7) are considered, and “RMS90($E_{jj}$)” is defined as the root mean square of the total reconstructed energy ($E_{jj}$) of the events lying within the smallest range of $E_{jj}$ which contains 90% of events. The energy resolution of each jet, “RMS90” is obtained by dividing “RMS90($E_{jj}$)” by $\sqrt{2}$. Since the reconstructed jets have tails due to the confusion of particles in the jets and usual “RMS” makes over-emphases of the importance of these tails, the “RMS’90” is frequently used in this fields.

7.1 Energy spectra

The PandoraPFA algorithm reconstructs particles included in jets, particle flow objects (PFOs), by clustering, checking association with tracks, and categorization in electromagnetic particles hadrons, and muons[1]. The energy of a jet is energy sum of those PFOs with a threshold discussed in section 4.
Figure 7 shows the total reconstructed energy ($E_{jj}$) at a center-of-mass energy of 200 GeV when using the $5 \times 5$ and $45 \times 5$ Sc-ECAL models, with and without the use of SSA. The shape of the energy spectrum for the $45 \times 5$ Sc-ECAL is noticeably improved by the use of SSA, and comes close to that of the $5 \times 5$ model.

Figure 7: Reconstructed energy in $q\bar{q}$ events at 200 GeV, for the $5 \times 5$ mm$^2$ ScECAL and the $45 \times 5$ mm$^2$ strip-ScECAL with and without the use of SSA.

### 7.2 Dependence on strip length

The dependence of the jet energy resolution at a center-of-mass energy of 200 GeV on the strip length is shown in Fig. 8. The same strip width of 5 mm was used in all models. The strong degradation in performance seen when SSA is not used is almost completely mitigated by the use of SSA. The difference in jet energy resolution between an ScECAL using $5 \times 5$ tiles and one using strips of length up to 60 mm is almost negligible.

Figure 8: Estimated single jet energy resolution of 100 GeV jets produced in $q\bar{q}$ events at a center-of-mass energy of 200 GeV. RMS90 is defined in section 7.1.
7.3 Comparison of 5×5, 45×5, and 15×15 ScECAL models

Figure 9 shows the jet energy resolution as a function of jet energy for a 45×5 strip-ScECAL without and with SSA, and 15×15 and 5×5 tile-ScECAL models. At smaller jet energies, below 100 GeV, the jet energy resolution is dominated by the intrinsic single-particle resolution, giving a resolution which improves with increasing energy$^2$. At energies above 100 GeV, the confusion between charged and neutral calorimeter clusters starts to become significant, leading to a degradation of resolution with increasing energy [1]. This behavior is seen for all ScECAL geometries. The jet energy of the 45×5 strip-ScECAL is significantly improved by using SSA, especially at energies above 100 GeV, indicating that the confusion is decreased by SSA. A tile of 15×15 has the same area as a 45×5 strip, however it is clear that the jet energy resolution when using the strip geometry is significantly better (by up to 0.5%), demonstrating the real merit of a strip-based geometry used in conjunction with SSA. The degradation in jet energy resolution between the 5×5 and 45×5 (with SSA) models is rather small, less than 0.25% for 45 GeV and 250 GeV jets, and around 0.1% for jets between 100 and 200 GeV as the absolute deviation values.

![Jet energy resolution of as function of jet energy for different tile- and strip-ScECALs.](image)

7.4 Jet energy resolution of strip-tile-ScECAL

As discussed in section 6.1, the major problem faced by a strip-based ECAL is the formation of ghost clusters. Therefore, the use of interleaving tile layers is expected to improve the jet energy resolution.

Figure 10 compares the jet energy resolutions of 45×5, alt5, and alt10 models. The performance of the alt5 and alt10 models are almost identical. At jet energies of up to 100 GeV, they give almost the same performance as the 5×5 model, while at higher energies the performance lies approximately half way between the 5×5 and 45×5 models. The fact that the effect of 5×5 mm$^2$ and 10×10 mm$^2$ tile layers are the same as each other is consistent with the result shown in Fig. 4 left that the ghost effect looks begin from 10 mm distance between clusters.

$^2\sigma_E/E$ of 3.5% at 50 GeV and 2.9% at 100 GeV is not consistent with $\sqrt{E}$ behavior. Probably, the confusion term starts to be significant even below 100 GeV.
8 Discussion

SSA successfully extracts fine granularity information, at an effective scale close to that of the strip width, from a strip-based calorimeter. The small degradation in jet energy resolution, around 0.2% as the absolute deviation value, when going from a 5×5 tile-ScECAL to a 45×5 strip-ScECAL can be almost completely recovered by the use of tile layers interleaved between the strip layers. These tile layers prevent the formation of ghost hits, as has been demonstrated in the reconstruction of a simple di-muon system.

Tile layers with a granularity of 10×10 mm$^2$ have been shown to work well. The use of such a tile size is technically feasible. The use of 15×15 mm$^2$ tiles, which have the same area as the 45×5 mm$^2$ strips currently being used in a prototype ScECAL, and therefore the same density of readout electronics, are certainly technically feasible. Studies of reconstruction performance with such larger tiles are continuing. The use of scintillator-based 5×5 mm$^2$ layers is technically difficult at present, but a different technology, such as the silicon readout ECAL being developed by CALICE [12], could be used.

The strip scintillator technology for ECAL presented in this paper could also be applicable for the hadron calorimeter. It must be a challenging and worthwhile research to apply this method to more complicated topology of hadronic showers.

MOKKA describes detail geometry of scintillator strips, dead volume comes from reflector, PPD packages, radiators, circuit boards, structure of the carbon frame. However, detail implementation and discussion of the effect of saturation phenomenon of PPDs, reduction of the statistics of photon in PPDs, nonuniform response of scintillator strip, and so on are ongoing. This study focus on the potential of the strip-energy splitting method.

9 Summary

An algorithm ("SSA") to extract fine granularity from scintillator strips was developed and tested. The reconstructed position of clusters was significantly improved with SSA: maximum shift of reconstructed position of 10 GeV photon clusters from true position with 45 mm strip-ScECAL is improved form 5 mm to sub-mm with SSA. Strip-ScECAL with SSA also shows comparable performance of particle separation of muon pairs and photons from $\pi^0$ samples to the performance of 5×5 mm$^2$ tile ScECAL. Excess clusters created by two particles incident into a square area with less than strip length, ghosts, are resolved by square tile layers alternately replaced with strip layers.
The energy resolution for jets of up to 250 GeV was compared among several types of ScECAL: ScECAL with 45 x 5 mm$^2$ scintillator strips, and with such layers alternately replaced with 5 x 5 mm$^2$ or 10 x 10 mm$^2$ tile layers. Differences in the obtained jet energy resolutions when using a 5 x 5 tile-ScECAL and 45 x 5 strip-ScECAL with SSA reconstruction ranged from 0.15% to 0.25% as the absolute deviation values. This difference can be removed for jet energies below 100 GeV, or decreased to ~0.1% for jet energies in the range 150 - 250 GeV, by alternately replacing strip layers with tile layers.

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