What does bring space granularity to calorimetry.

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Abstract. The development of calorimetry for the linear collider has led to a dramatic increase of granularity with respect to previous detectors. This appeared as mandatory in the framework of the so-called "particle flow approach". What does really provide granularity? Is there an optimal granularity? This will be discussed as a function of the energy reach under consideration for the electromagnetic component as well as the hadronic one.

1. Introduction
The development of calorimetry for the linear collider has led to a dramatic increase of granularity, by a factor of about 1000 shared almost equally between directions along the showers and transverse to them. This raises few questions like, which accelerator, which physics conditions, which technological evolutions have enabled this? What is really the purpose, is there any future pursuing this way and in particular is it a key for going to higher energies?

Trying to figure out what does really provide granularity, we can examine the role it plays in electromagnetic calorimetry and then what can be expected on hadron calorimetry from the point of view of energy measurement accuracy, sensitivity to calibration or leakage.

2. Conditions of operation
Using small detecting cells read independently implies embedding the front-end electronics in the detector while integrating in this front-end functionalities like self-triggering, digital storage or huge level of multiplexing. This may also help keeping the cost reasonable. Such a constraint has as a consequence the generation inside the detector of heat which has to be drained out. An accelerator like ILC [1], with a reduced up-time may allow pulsing the power which can reduce by a factor 100 the heat generation. This is a key to the development of highly granular calorimetry, but pulsing in the presence of a 3.5 T field is another challenge. The embedding of the front-end in the detector induces also a severe constraint on the quality assurance which has to be almost at spatial level, this has a cost but is well documented.

3. The electromagnetic calorimetry
The purpose of electromagnetic calorimetry for the physics at ILC is to look for photons and electrons within jets of particles. Hence the goal is to measure their energy, position or angle once they have been properly identified, separated from neighbour photons or hadrons. Then the prime accomplishment is to make the pattern of electromagnetic showers as distinguishable, as discernible as possible. The electromagnetic showers are rather well characterised but have fluctuations, tails and halo which have to be handled in a crowded environment. Can it be
expected to clean the shower to its core while keeping the energy resolution and this by playing on cell thresholds and on clustering algorithms? Trying this speaks for longitudinal as well as transverse granularity.

Restricting to sampling calorimetry it is well known that, for isolated showers, the energy resolution is directly linked to the sampling, which does not imply a longitudinal read-out grain size. The position and angle measurement precisions are in turn dictated by the energy resolution provided the cell position is properly known and the cell size well below the Molière radius. In jets, before measuring any property, the photons have to be separated from hadrons or other photons. This statement can be qualified. Is there any point in distinguishing two close by photons, or finding \( \pi^0 \)'s? Not really because that will not modify much the energy or momentum of the system. The only specific case may be to sign the tau decay modes to be able to measure polarisation or spin correlations. Confusing photons with adjacent neutral hadron may hamper the jet signature but will enter the global energy measurement only through the difference in response to a photon and a hadron. But confusing a photon with a charged hadron in the framework of the “particle flow analysis” (PFA [2]) induces double counting hence a first order error on energy. A mixture of photons may also be more likely to be confused with a charged hadron shower left over. The figure 1 [3] provides the probability for such confusion between a charged track and a near-by photon, this is done for 250 GeV u/d/s jets. For example 3% of the photons have a charged track hitting the calorimeter at less than 20 mm. Taking into account the number of photons suggests that a separation better than 20 mm is needed.

![Figure 1](image)

**Figure 1.** Average fraction of photons in a 250 GeV jet with a charged track closer than \( d \) as a function of \( d \).

### 3.1. Parameters to play with for shaping the showers

The figures shown in this section come all from simulation of 10 GeV photons in the ILD [4] electromagnetic calorimeter which is a sandwich of tungsten radiators and silicon sensors. The cell size has been chosen for this study to be 1 mm\(^2\).

The figure 2 shows that at such a level of granularity the characterisation of the shape is not totally trivial, it shows also that the density of hits outside the Molière radius is reduced. The spectrum (figure 3) exhibits mostly few MIP peaks convoluted with Landau distributions. The radial energy distribution provides the effective Molière radius for the given detector structure at about 17 mm. On the figure 5 the radial energy density is shown, it is basically the previous distribution divided by the radius; it appears that the core of the shower is very narrow, 2 to
3 mm diameter suggesting that identifying a track from a nearby photon can be done at very short distance.

![Image](image1.png)

**Figure 2.** View of a shower, the two lines materialise the Moliere radius.

![Image](image2.png)

**Figure 3.** Energy spectrum of the shower cells.

![Image](image3.png)

**Figure 4.** Radial distribution of the energy.

![Image](image4.png)

**Figure 5.** Radial distribution of the density of energy.

To adjust the detected shower shaping, it is possible to play with the detector structure, i.e. the Moliere radius, and on the read out or grain size. It is difficult to dream improving by going to a material denser than W at an acceptable cost. A thinner detecting medium can be envisaged but the measured Moliere radius is only a factor 1.7 above pure tungsten. The only real degree of freedom is the grain size and its impact has to be assessed. The cell threshold could also be considered but is heavily linked to the size in the cell range under consideration.
3.2. Separating nearby photons

As seen earlier, the core of the shower in this calorimeter model is about 3 mm diameter. Identifying two photons is being able to separate a real photon from a fluctuation of a nearby one. The question is then about the probability that in a given domain few mm$^2$ wide at a given distance of the main photon there be a significant fluctuation. This is clearly dependent on the energy of both photons but the cell size has anyway to be adapted to the core size and not to the Moliere radius, a mm level. This is illustrated in figure 6 showing that two photons of about 20 GeV each can readily be separated 12 mm apart with a millimeter grain size.

![Figure 6. 100 GeV tau decaying into $\rho$ seen with a 1 mm$^2$ grain. The cell energy is coded by a colour scale from blue to white.](image)

![Figure 7. Display of the energy deposited by closeby photon and pion. The energy is coded by a scale from brown to white.](image)

3.3. Separating photons from a nearby charged hadron

The problem here is to disentangle the photon from the track and its shower in order to avoid losing the photon energy or doubly counting part of the hadron energy. The strategy will depend on the interaction depth in the calorimeter. For a track long enough the characteristic shape is not anymore the shower shape but the track shape and the cell size limit is the transverse size of a track provided by the multiple scattering. This situation is illustrated on figure 7. To be more precise, the question is to know what is the probability to find $n$ aligned fired cells at a given distance from the photon. Figure 8 provides the hit radial density of a 10 GeV photon for 1 mm$^2$ cells, the peak height being 13 cells. It can be seen that, even without looking at the longitudinal distribution of the hits, a track leaving at least 5 hits can be separated at few mm’s.

3.4. Miscellaneous properties

Going to small cell sizes reduces slightly the cell response dynamics, 1 bit by going from 25 mm$^2$ to 1. At some point counting the hits will provide adequate energy measurement in most of the energy domain and anyway helps the energy measurement at low energies by killing the Landau tails. But this has a limit when the cell size reaches the length of delta rays propagating in the sensitive medium. There is an optimal cell size for counting.
4. The hadronic calorimetry

The problem here is to disentangle in jets the neutral hadrons from the majority of charged hadron showers, then to measure them at best which means mastering the resolution, the calibration and the leakage. Once you go below the hadronic shower size, of the order of 10 cm, the only relevant size is the track size. It is then tempting to adapt the calorimeter at looking at tracks inside the calorimeter. This may provide a lot of improvements. Identifying tracks in the showers and measuring their momenta, up to the multiple scattering, provides: a resolution improvement by weighing the electromagnetic versus hadronic components, an in situ calibration of efficiency, a way to reduce the sensitivity of the digital measurement to efficiency and multiplicity, an improvement of the shower separation by following or measuring the charged links, an improvement of the leakage estimation by measuring the momenta of tracks leaving the calorimeter.

To characterise the issue, the figure 9 (courtesy of J-C. Brient) shows the energy distribution of the $K^0_s$ and neutrons produced in 500 GeV jets of any kind except tops, produced through a Z without radiative return. 8% of these neutrals have more than 100 GeV. It can be expected that the leakage in these cases is large but the interaction probability stays the same. Does the use of the fine grain calorimeter as a true tracking calorimeter help here?

With 7 interaction lengths the sail through reaches 0.1% quite independently of the energy. The sail through is illustrated in figure 10 (be aware that the horizontal and vertical zoom factors are different). Those neutrals which interact produce second level neutrals and charged particles. The probability to have these second level neutrals escaping in turn is about 1% of their probability to be produced. The leakage is therefore linked mostly to charged particles. Why not try then to use our fine grain calorimeter truly as a tracking calorimeter profiting of the strong field and of the measurement accuracy limited though by the multiple scattering. In fact such an approach was used already in ALEPH for identifying the muons through their momentum measured in the return field.

This has been looked at with 1000 20 GeV $K^0_s$’s sent into the ILD calorimeter in its digital option as simulated with MOKKA [5] for a grain size of 1 mm$^2$. A beautiful example is shown in figure 11 where the interaction takes place in the electromagnetic part. The charged kaon in pink has 14.5 GeV.
But not only the tracks escaping can be measured, any charged secondary can be and in many cases this measurement will be better than the energy of the corresponding shower, improving the global calorimeter resolution. In our corpus of events 6.5% had a leakage larger than 2.5%. A simple procedure of fitting was able to save 2/3 of them, this is equivalent to spare one interaction length. The method was rather heuristic and needs development.

A 1 mm$^2$ grain may look like a dream. In view of the fact that it is used for the hadronic part in a digital mode, the main problem is probably with the connections. The data flow is not a problem, the number of cells hit does not grow by far like the inverse of the areas and the flow remains very limited at ILC. More precisely in a 10 GeV electromagnetic shower the number of cells hit grow by a factor 2 when going from 25 mm$^2$ to 1 mm$^2$ cells.

5. Conclusion
A very fine grain calorimeter helps disentangling the components of the jets and of the showers improving the resolution. Identifying properly the tracks in the showers provides a way to calibrate the detector in situ and to palliate the inefficiencies. The high field provides an adequate measurement of the charged particle momenta helping to control the leakage in the barrel. We should consider going for a true tracking calorimeter bringing PFA into the showers.

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