**SYSTEMATIC INVESTIGATION OF
THE LOCAL HARDENING EFFECT
AND LATERAL ELECTROMAGNETIC-SHOWER DEVELOPMENT**

SICAPO Collaboration

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Abstract

In silicon sampling calorimeters, a local hardening effect occurs when inserting a small thickness of low- Z material next to the thin active layer. This effect, which appreciably modifies the electromagnetic response, allows control of the relative responses to hadronic and electromagnetic showers. A thorough study of lateral shower profiles has been undertaken to improve the precision of the measurement of the absolute electromagnetic response. The main features of the local hardening effects as a function of the thickness of low- Z material are explained by a $1/E$ distribution of ionizing particles inside the shower, whilst those of the lateral profile are explained by an exponential radial distribution.

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1 Introduction

Maintaining an equal response to electrons (e) and pions (π) of a given energy [1] is an absolute necessity in order to obtain good resolution in calorimetry at very high energies. In a *compensating* calorimeter, the condition $e/\pi = 1$ is satisfied, where e indicates the average response of the calorimeter to incoming electrons (and photons), and π designates the average response of the calorimeter to incoming pions (and other hadrons). The SICAPO Collaboration is investigating the use of silicon sampling calorimeters as potential compensating calorimeters in the next generation of accelerators.

2 The local hardening effect

The response (signal produced per incoming energy given off) of both electrons and pions is different from the response of a particle simply losing energy by ionization (mip = minimum ionizing particle). Writing the e/π ratio as $(e/mip)/(\pi/mip)$, an improved understanding of the effects, affecting specifically the electrons and the pions, is obtained.

The ration π/mip depends on the energy (since the fraction of electromagnetic shower inside a hadronic shower varies with energy), and it can be increased by adding hydrogenous material near the readout [2] and to a lesser extent, by using fissionable material as absorber [3].

The present discussion will focus on the effects which permit one to decrease the e/mip ratio. The response of the calorimeter to the electromagnetic component of a shower is decreased by sampling the shower at a point where its soft component is strongly suppressed owing to the insertion of low atomic number (low- Z) material in the sandwich structure. This is called *the local hardening effect* [4]. In the SICAPO calorimeter, the low- Z material is G10, a commercially available mixture of fibreglass and epoxy. It is important to note that since we use high- Z absorbers (W, Pb, U), with critical energies much lower than 21 MeV, the multiple scattering is very important, the average track angle with respect to the shower axis is large, and many particles are going backwards. Thus a reduction of e/mip is achieved when G10 is inserted *behind* the silicon sampling plane. This is also obtained when G10 is inserted in front of the silicon sampling plane. However, the backward-going electrons being on an average softer, the local hardening effect is more pronounced when thicknesses of G10 are inserted *behind* rather than in front of the silicon sampling plane [1]. The effectiveness of the local hardening effect in controlling the electromagnetic response is illustrated in Fig. 1, which shows the relative reduction of the response to electromagnetic showers as a function of the thickness of G10 inserted both in front of and behind the silicon sampling plane in a Pb/Si sampling calorimeter.

It appears that, with a thickness of 5 mm G10 acting as a low- Z filter, a reduction of the electromagnetic response of 40% can be obtained with respect to the situation where the silicon is immediately behind the high- Z absorber.

It is interesting to note that this reduction, which can be measured experimentally, approaches a logarithmic curve. The intuitive reason is as follows: given that a large fraction of the energy deposited in the silicon is deposited by low-energy photoelectric electrons, which have a $1/E$ distribution of energy, and therefore a $1/R$ distribution of range, the number of electrons able to cross a certain thickness t_{G10} of low- Z material is an integral of the range distribution, thereby resulting in a logarithmic form:

$$(e/mip)_0 - e/mip = K \ln \left(\frac{t_{G10} + t_{Si}/2}{t_{Si}/2} \right).$$

Figure 1: Reduction of the electromagnetic response as a function of the thickness of G10 inserted in front of and behind the detectors. The continuous line shows the logarithmic form.

The lower bound of this integral ($t_{\text{Si}}/2$) is determined by the fact that very soft electrons range a distance less than the remaining thickness of the silicon.

3 Lateral shower development

A systematic experimental study of the lateral shower profile has been performed to measure the shower parameters in a broad range of experimental conditions. The shower was sampled at 2, 4, 6, 8, 10, and 12 radiation lengths longitudinal coordinate, for beam energies of 2, 4, and 6 GeV. In addition, the critical energy of the high- Z absorber has been varied by using uranium and tungsten as absorber materials, and the possible modification of the lateral shower profile induced by the insertion of G10 has also been investigated by carrying out the measurement without G10, and with thicknesses of 1, 3, and 5 mm of G10.

The calorimeter used for these tests consists of a longitudinal assembly of $5 \times 5 \text{ cm}^2$, 2 radiation-lengths-thick absorbers (made of either W or U). In between the absorber blocks are the sampling planes, consisting of $4.8 \times 4.8 \text{ cm}^2$ silicon planes and optional $5 \times 5 \text{ cm}^2$ G10 plates. The silicon sampling plane is a $190 \mu\text{m}$ thick n-type silicon wafer, fully depleted, and read out by 48 strips of 1 mm pitch. The experimental set-up is completed by a scintillator/photomultiplier coincidence trigger, making a ‘telescope’ to ensure that we only record particles impinging in the middle of the calorimeter.

For an accurate estimate of e/π , a precise understanding of the lateral losses of electromagnetic showers is needed. These losses can occur at the interstices between wafers, or as energy leaks out of the sides of the calorimeter.

Previous studies of the lateral shower development have been focused on the slope and height of the exponential tail [5] of the radial distribution of deposited energy. Nonetheless, the experimental shower profile is more complex than a mere exponential; even if the radial distribution was precisely the exponential form explored in Ref. [5], a first complexity arises in the present case because we are studying the distribution of the energy deposited in a series of strips, which represents a particular folding of the radial distribution. Supposing the radial distribution dE_{dep}/dr is an exponential e^{-r/r_0} , then the

lateral distribution

$$\frac{dE_{\text{dep}}}{dx}$$

is a Bessel function

$$\begin{aligned} \frac{dE_{\text{dep}}}{dx} &= \int_{-\infty}^{+\infty} dy \frac{dE_{\text{dep}}}{dx dy} = \int_{-\infty}^{+\infty} dy \frac{1}{r} e^{-r/r_0} \\ &= \int_{-\infty}^{+\infty} dy \frac{1}{\sqrt{x^2 + y^2}} e^{-\sqrt{x^2 + y^2}/r_0} = K_0\left(\frac{x}{r_0}\right). \end{aligned}$$

Thus an exponential radial distribution is seen to correspond to a Bessel lateral distribution. As can be seen in Fig. 2, this Bessel form fits the data well at large shower ages (8,

Figure 2: Lateral shower profile of the electromagnetic shower produced by 6 GeV electrons impinging on the W/Si calorimeter with no G10. The vertical axis gives the energy deposited in each strip with a logarithmic scale. The continuous lines show the fitted Bessel functions $BK_0[A(x - x_0)]$.

10, 12 radiation lengths), but at longitudinal coordinates, of 2, 4, and 6 radiation lengths, it is not able to reproduce the shower profile either in the centre or in the tail.

Furthermore, a linear sum of two Bessel functions of different slopes has been considered. The fit to the data is rather good (see Fig. 3), but the four parameters thus obtained are difficult to interpret physically. As observed previously, both a narrow and a wide components are needed to describe completely electromagnetic lateral shower profiles [6].

Figure 3: Lateral shower profile of 6 GeV electrons for W/Si with no G10. The continuous lines show the fitted linear sums of Bessel functions $BK_0[A(x - x_0)] + CK_0[D(x - x_0)]$.

Figure 4: Widths $1/A$ of the Bessel fit to the electromagnetic shower profile as a function of the depth in radiation lengths with a W absorber, at 2 GeV with no G10 ($\circ$), at 4 GeV with no G10 ($\square$), at 6 GeV with no G10 ($\blacktriangle$), and at 6 GeV with 5 mm G10 ($\bullet$).

A concise summary of all our results with W absorbers is shown in Fig. 4.

The slope of the Bessel function fitted to the data is shown as a function of the longitudinal coordinate, for a variety of conditions of beam energy and thickness of G10. It is observed that the size of the shower increases monotonically with the longitudinal coordinate. The evolution can be fitted with the form proposed by De Angelis (continuous curve), although the data hint at a more pronounced broadening with increasing shower depth. No net tendency is observed as a function of beam energy. Remarkably, although the effective radiation length increases significantly by inserting G10 (from 3.5 mm without G10 to 6 mm with G10, in the case of W), the transverse size of the shower is not observed to increase. The general features of the shower are apparently not modified by insertions of low- Z material, and are dominated by the characteristics of the high- Z material.

4 Conclusion

The systematic measurement of the lateral shower profile and the local hardening effect provide all the tools needed to measure and control e/mip . This, together with an equivalent knowledge of π/mip , enables us to obtain the compensation condition $e/\pi = 1$.

In order to make it easier to use the lateral profile data shown here, their compact parametrization would be very useful. It was shown that the lateral equivalent of a radial exponential is a Bessel function, and this function was observed to fit the data at large shower depths (6, 8, 10, and 12 radiation lengths). This form can be extended to a linear sum of two components in order to fit the data at 2 and 4 radiation lengths. As previously observed, both a narrow and a wide components are needed to describe completely electromagnetic lateral shower profiles [6].

Finally, it was observed that the lateral shower profile is virtually not modified by insertions of large thicknesses of G10, which increase the effective radiation length by a factor of about 1.71.

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