EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/89-65

8 May 1989

**ELECTROMAGNETIC SHOWER ENERGY FILTERING EFFECT:
A WAY TO ACHIEVE THE COMPENSATION CONDITION ($e/\pi = 1$)
IN HADRONIC CALORIMETRY**

SICAPO Collaboration

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ABSTRACT

Equalization between the electromagnetic and the hadronic signals is the condition for obtaining the linear response of a calorimeter to hadronic showers and an energy resolution that improves as the incident energy increases. In a calorimeter with silicon readout, the use of a combination of low-Z and high-Z materials as absorbers allows the transformation of the electron energy distribution of the incident showers in two media with different critical energies. As a result, the response of the calorimeter to incoming showers is modified to achieve the compensation condition ($e/\pi = 1$).

(To appear in Physics Letters B)

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1. INTRODUCTION

The SICAPO Collaboration (Florence, Hamburg, McGill, Messina, Milan, Oregon, Tel Aviv, Tennessee, Trieste, Turin) is involved, since a few years, in the study of the compensation properties of hadron calorimeters to be used in experiments at the next generation of colliders. The possibility to observe many of the phenomena of interest at these colliders depends critically on the intrinsic resolution of the calorimeters in operation in the planned experiments. The performance of hadron calorimeters is determined by the relative response to the electromagnetic and non-electromagnetic shower component, the e/π signal ratio. Equalizing the response of the calorimeter to electrons and hadrons ($e/\pi = 1$, i.e. the compensation condition) is the requirement for reaching optimal performances of the calorimeter. The physics goals and the processes that limit the effective resolution fix the energy resolution of a compensating calorimeter at $\sigma/E \approx 50\%/\sqrt{E}$ [1]. In a previous letter [2], a new approach to the realization of the compensation condition has been proposed, taking the point of view that it could be reached by decreasing the response of the calorimeter to the electromagnetic part of the shower. This has been achieved by the effect of local hardening [2], where the soft incoming electromagnetic shower component and the flux of backward-going electrons (resulting from multiple scattering in the high-Z absorber) are dumped by low-Z (G10) plates inserted between the active and the passive media. Experimental evidence for this local hardening has been observed and measured up to G10 thicknesses of 5 mm (2.5% of radiation length).

In the present letter, we demonstrate that the signal equalization that provides the condition $e/\pi = 1$ is realized in a calorimeter with silicon readout and with Fe and Pb as the passive media (where the thickness of the low-Z material is no longer small compared with that of the high-Z material). The combination of low- and high-Z materials in the absorber leads to an electromagnetic shower energy transformation effect, generated by a sharp transition from small to large values of the critical energy [$\epsilon = 2.66 (ZX_0/A)^{1.11}$; X_0 is the radiation length in g/cm²] [3]. The value of ϵ (21.0 and 7.4 MeV for the Fe and Pb absorber, respectively) is the value of the electron energy below which the ionization energy loss starts to dominate the energy lost by radiation. Therefore the lower the critical energy of the absorber, the softer is the energy spectrum of the electromagnetic showers, when entering a low-Z (Fe) absorber and exiting from a high-Z (Pb) absorber. As a result, the energy distribution of the shower is transformed and the response of the calorimeter to the incoming shower is dramatically modified. The degree of the effect obviously depends on the fraction of Fe and Pb in the absorber. Therefore the fraction of Pb in an absorber made of a combination of Fe and Pb, will play an important role in the phenomena described below. Furthermore, the low-Z Fe and the high-Z Pb absorbers have very different radiation lengths (1.76 and 0.56 cm, respectively) but similar interaction lengths (16.8 and 17.1 cm, respectively). Then, even if the passive medium of a hadron calorimeter consists of a low-Z absorber with a thickness smaller than (or comparable to) that of the high-Z material, in units of radiation lengths, the low-Z material may very well be the thickest when computed in units of interaction lengths.

The energy resolution of a sampling hadron calorimeter can be generally written as

$$\sigma/E = C/\sqrt{E} + f[(e/\pi) - 1] ,$$

where $\sigma = (\sigma_{\text{bind}}^2 + \sigma_{\text{samp}}^2)^{1/2}$ contains the contribution from the intrinsic fluctuations due to nuclear binding energy losses (σ_{bind}) and that from the sampling fluctuations (σ_{samp}); $f(e/\pi)$ is energy-dependent as a result of the logarithmic increase, with energy, of the total number of π^0 in a shower initiated by hadrons [$\langle n \rangle \approx 5 \ln E(\text{GeV}) - 4.6$] [4], and is vanishing only if $(e/\pi) = 1$. For a given absorber, the sampling fluctuations can be easily modified and eventually decreased by changing the frequency of the sampling [i.e. changing the number of active planes per interaction length (λ)]

and/or changing the ratio between the relative thicknesses of the readout and the absorber. The contribution to the resolution, σ_{bind} , is sensitive to the number of neutrons released by the absorber per GeV of incident energy and, being then intrinsic to the absorber material, it can be minimized by the proper choice of material. For instance, $\sigma_{\text{bind}}/E = 40\%/\sqrt{E}$ for uranium absorber and $18\%/\sqrt{E}$ for Fe [5]. The concept of a calorimeter with an Fe-dominated absorber (and a small fraction of high-Z metal, which we will determine in the following) appears to be the way to reach a resolution of $\sigma/E = 50\%/\sqrt{E}$ as requested by the physics goals to be achieved by the experiments at the next generation of colliders.

2. EXPERIMENTAL SET-UP AND DATA

A silicon sampling electromagnetic calorimeter (i.e. a calorimeter in which the absorber-material plates alternate with readout silicon detector planes) has been set up to investigate the calorimeter response to the electromagnetic component of the incoming shower. The calorimeter consists of ten absorber plates of variable length (of Fe and/or Pb absorber) interspaced with silicon readout mosaics. The total calorimeter depth varies from a minimum of 20 radiation lengths up to 50. The readout mosaic planes (with an active area of $\sim 250 \text{ cm}^2$) are made of trapezoidal silicon detectors [6] built by Ansaldo, Italy. A trapezoidal detector has an area of about 28 cm^2 and is $400 \mu\text{m}$ thick. The detectors are operated at a depleted-layer width of $200 \mu\text{m}$. The mosaic planes are mounted on a G10 support (0.2 and 1.0 mm thick at the front and the rear of the detector, respectively). The use of serial coupling of five silicon detectors, while reducing the number of electronic channels and the overall detector capacitance, allows us to employ fast electronics (about 100 ns base-time signals) with a wide dynamical range (five decades). The data have been taken at the CERN Proton Synchrotron (PS) t_9 beam. The incoming electron energies were 2, 4, and 6 GeV. A gas Cherenkov counter, filled with helium at $1.4 \times 10^5 \text{ Pa}$ was used to select electrons. A beam scanner, consisting of a scintillator counter of $0.5 \times 0.5 \text{ cm}^2$ area, ensured that only electrons impinging on the middle of the calorimeter triggered. The absolute energy calibration has been performed following two independent approaches: i) by using ^{241}Am α sources (5.48 MeV) [2]; ii) by means of minimum-ionizing particles (μ), which give a well-known energy-loss distribution in the silicon readout detectors. The two methods agree well, and the error on the absolute energy scale is about 2%. Our measured visible energy (ϵ_{vis}) has to be corrected for the energy losses in the dead zones between the detectors in the mosaics. For both the Fe and Pb absorbers, the total lateral energy loss amounts to $(3.4 \pm 1.0)\%$ of ϵ_{vis} . This correction has been calculated from previously measured lateral energy distributions [7].

3. ELECTROMAGNETIC SHOWER ENERGY FILTERING EFFECT

The ratio e/mip measures the energy deposited in the sensitive part of the calorimeter by electron and photon showers relative to minimum ionizing particles (mip) depositing all their energies in collision losses in a similar, but indefinitely extended, calorimeter, and is defined as

$$e/\text{mip} \equiv \epsilon_{\text{vis}}/E_s ,$$

where ϵ_{vis} is the visible (electromagnetic) energy measured in the calorimeter, and the energy shared by the minimum-ionizing particle in the silicon detectors (E_s) is given by

$$E_s = (dE/dx)_{\text{Si}} X_{\text{Si}} E / [(dE/dx)_{\text{Si}} L_{\text{Si}} + \Sigma (dE/dx)_i L_i] ,$$

with X_{Si} , L_{Si} , L_i , $(dE/dx)_i$, and E being the depletion depth, the thickness of the Si detector, the thickness of the absorber i , the average energy loss per unit of length in the absorber i , and the incoming particle energy, respectively.

One can generally write $\epsilon_{vis} = K/\tau + f(\tau)$, where $f(\tau)$ is a smooth function of the sampling frequency τ (the thickness in units of radiation lengths of passive material interspaced between two active samplers). The quantity $\epsilon_{vis}\tau$ is shown in fig. 1 as a function of the sampling frequency τ , and for both Fe and Pb it can be seen that $\epsilon_{vis}\tau$ does not show any dependence on the sampling frequency, within the experimental errors. The values of ϵ_{vis} , measured for incoming electrons of 4 GeV, include the correction for the energy lost in the mosaic dead areas.

The response of the electromagnetic sampling calorimeter has been investigated by joining Fe and Pb absorbers in between the readout silicon mosaics. The overall τ value takes into account the thicknesses of the Fe (of a fixed $1.99X_0$ length) and Pb absorbers. In this way, a τ increase corresponds to a lowering of the effective critical energy. Thus the value of $\epsilon_{vis}\tau$ versus τ is expected to be increased from its value corresponding to pure Fe absorbers to that for pure Pb absorbers. However, different absorber configurations (in which the silicon readout mosaics are located either in front or at the rear of the Pb absorbers, or in between them) can be realized. The sensitivity of the visible energy to the sampling frequency and configuration is shown in fig. 1, where $\epsilon_{vis}\tau$ is given as a function of τ . In absorber material configurations such as FePb-Si-FePb and PbFePb-Si-PbFePb where the forward-generated electrons in Pb can enter the silicon detectors directly, a substantial increase of $\epsilon_{vis}\tau$ is measured (as expected). However, for the configuration PbFe-Si-PbFe (where the forward-generated electrons in Pb enter the Fe absorber) the measured values of $\epsilon_{vis}\tau$ increase only slightly. In fig. 2, the values of e/mip are given as a function of the Pb fraction f in the passive absorber ($f \equiv L_{Pb}/[L_{Pb} + L_{Fe}]$). There is an increase of the e/mip value up to $f \approx (5-8)\%$ in the absorber configuration where again the forward-generated electrons in Pb can enter the silicon detectors directly. The e/mip ratio for PbFe-Si-PbFe is decreasing steadily and is equal to 0.60 ± 0.02 at $f \approx 0.36$ ($\tau \approx 5.57$). Furthermore, in our case where $L_{Fe} = 35$ mm and $\tau = 1.99 + 6.25/(1/f-1)$, the experimental data show that the e/mip values for this configuration decreased with the increasing sampling fraction τ . This behaviour indicates that when low-Z Fe and high-Z Pb absorbers are joined, there is a deep modification of the absorption properties of the electromagnetic shower.

These data have to be compared with the e/mip values (with no corrections for the 1.2 mm G10 supporting the mosaic structure) for Pb and Fe absorbers: 0.78 ± 0.02 (at $\tau = 1.99$) and 0.74 ± 0.04 (at $\tau = 3.98$) for Fe, and 0.69 ± 0.04 (at $\tau = 1.96$) and 0.66 ± 0.04 (at $\tau = 3.39$) for Pb. The data—in particular those for the PbFe-Si-PbFe configuration—suggest that the electromagnetic shower generated in the Pb sampler (with $\epsilon = 7.4$ MeV) is filtered by the Fe sampler ($\epsilon = 21.0$ MeV). In fact, the mean energy of the electrons of the electromagnetic shower generated in the Pb material is lower than the critical energy of the Fe absorber. Consequently, these electrons undergo mainly collision losses in Fe, where they are easily absorbed. An appropriate use of this filtering effect on electromagnetic showers allows the calorimeter response to the electromagnetic component of a hadronic shower to be modified in order to achieve the compensation condition.

4. COMPENSATING CALORIMETRY

The ability to modify $(e/mip)_{Fe+Pb}$ with the fraction of Pb in the absorber leads to the possibility of tuning the e/π ratio. The ratio e/π is defined as

$$e/\pi = (e/mip)/[(e/mip)f_{em} + (h/mip)(1 - f_{em})] ,$$

where $(1 - f_{em})h$ is the visible hadronic energy, i.e. the energy deposited in the detector readouts by the purely hadronic component of the shower (see ref. [1] and references therein); f_{em} is the average fraction of hadron energy deposited by the electromagnetic shower in the calorimeter. For an incoming particle with energy E in a calorimeter with a constant sampling frequency along the particle direction, the h and e calorimeter responses (the latter being given by ϵ_{vis}) are linearly dependent on E , as well as on the mip value given by E_s . In the above equation it may be noticed that the e/π energy dependence is due to that of f_{em} . Furthermore, if the e and h calorimeter responses are intrinsically equal ($e/h = 1$), the e/π ratio is equal to the unit independently of f_{em} and of the incoming energy.

Recent Monte Carlo predictions [5] for a sampling calorimeter with a 3 mm thick Pb absorber and 400 μm thick silicon readout exposed to a 10 GeV π^- beam, give $e/\pi = 1.16$, $e/\text{mip} = 0.75$ and $h/\text{mip} = 0.62$ for $f_{em} \approx 0.25$. For Fe, the estimate is $(h/\text{mip})_{Fe} \approx 0.68$. Indeed, it can be expected that $(h/\text{mip})_{Fe} > (h/\text{mip})_{Pb}$ since, owing to a higher Z/A fraction and lower Coulomb barrier ($\sim Z \cdot A^{-1/3}$) in Fe compared with Pb, a smaller fraction of the hadronic energy is spent on ionization, and a larger fraction goes into neutron production in a Pb absorber than in an Fe one. In terms of visible energy, we have in general

$$\epsilon_{vis} = (e/\pi) \{ (h/\text{mip}) E_s (1 - f_{em}) / [1 - (e/\pi) f_{em}] \} . \quad (1)$$

In the case of an absorber composed of Fe and Pb, h/mip is given by

$$(L_{Pb}/\lambda_{Pb})(h/\text{mip})_{Pb} + (L_{Fe}/\lambda_{Fe})(h/\text{mip})_{Fe} . \quad (2)$$

At 4 GeV the comparison of ϵ_{vis} obtained from eq. (1) (when the compensation condition $e/\pi = 1$ is satisfied) with ϵ_{vis} measured for the PbFe-Si-PbFe configuration will provide the exact proportions of Pb and Fe that are necessary in order to provide the compensation condition. The exact fraction of Pb ($\sim 25\%$) needed to achieve this will be indicated at the crossing point of the two lines (see fig. 3). The insertion of G10 (and therefore the exploitation of the local hardening effect) will change the position of the crossing point, since a term $(L_{G10}/\lambda_{G10})(h/\text{mip})_{G10}$ has to be added to formula (2), and above all there are soft backward-scattered electrons that are absorbed by G10 and thus do not enter the Si detectors. Furthermore, the h -signal has to take into account the neutrons (generated in the hadronic cascade shower) interacting on the protons inside the G10 material. This results in a smaller fraction of Pb being needed in the absorber to achieve the compensation condition. In fig. 4 we show the reduction of the electromagnetic shower energy (which is due to the local hardening effect [2]), for the PbFe-Si-PbFe configuration when low- Z G10 absorbers, 5 or 10 mm thick, are inserted in the back of the Si detectors (i.e. in front of the high- Z Pb absorbers). The compensation condition is expected to be satisfied with $f \approx 13\%$ or $\approx 11\%$ for 5 or 10 mm thick G10, respectively (the f values are 15% and 13% respectively, if the h -signal enhancement, due to neutron interactions in G10, is neglected). The visible (electromagnetic) energy measured for an Fe absorber $1.99X_0$ thick is shown in fig. 5 as a function of the incident energy (E in GeV). The result of the measurement of ϵ_{vis} with Pb absorber plates $3.39X_0$ thick is shown in fig. 6. In both cases the calorimeter response is linear.

As an alternative solution, the signal equalization that provides the condition $e/\pi = 1$ can be realized in a calorimeter with pure Fe (or pure Pb) as the passive medium and with a silicon readout. The total energy sensed by this readout is reduced through the local hardening effect [2], which consists in the absorption of soft electrons by low- Z absorber (G10 plates) inserted in front and/or at the rear of the silicon detectors (i.e. to exploit the local hardening effect).

As pointed out earlier [2], in the course of shower development a large fraction of the energy goes into the production of low-energy photons. These soft photons interact almost exclusively in the

absorber, and most of the soft photons will transfer their energy partly (Compton effect) or totally (photoelectric effect) to the electrons of the absorber. The low-energy electrons, produced by the conversion of low-energy photons very close to the surface of the absorber, can escape and contribute to the measured signal. However, these low-energy electrons can be multiply scattered. In Pb (high-Z), the low-energy electrons form larger angles [$\langle \cos \alpha \rangle = \cos(21 \text{ MeV}/\epsilon\pi)$] [4] with respect to the shower axis than in Fe (low-Z). The number of large-angle electrons is large in Pb and small in Fe. The multiply-scattered electrons have a path length ($d/\langle \cos \alpha \rangle$) that is relatively longer in Pb than in Fe. Our results show that in Pb the effect of G10 on the back-scattered electrons is twice as large as in Fe. Thus the effectiveness of the local hardening effect will be about twice as important in Pb absorbers, as compared to Fe absorbers. However, the probability of neutron interaction on free protons (G10 material contains hydrogen atoms) becomes greater when the thickness of the low-Z G10 plate is augmented. As a consequence, the increase of the hadronic signal can no longer be neglected.

5. e/mip RATIOS; Si/Pb AND Si/Fe HADRONIC CALORIMETRY

The G10 supporting mosaic structure generates a local hardening and therefore reduces the measured deposited energy in the silicon mosaics themselves. The effect of the 1.2 mm of the G10 supporting structure on ϵ_{vis} has been evaluated by measurements carried out with and without G10 absorbers in Si/Cu (a value of Z close to that of Fe) and Si/Pb calorimeters [8]. It has been found that the visible energy measured with the mosaic structure has to be increased by $(5.6 \pm 1.0)\%$ and $(10.0 \pm 1.0)\%$ for Fe and Pb absorbers, respectively. Therefore the visible (electromagnetic) energy (fig. 1) for Fe and Pb at $\tau = 1.99$ and 4 GeV is

$$\epsilon_{\text{vis}}(\text{Fe}) = (6.17 \pm 0.16) \text{ MeV} ,$$

$$\epsilon_{\text{vis}}(\text{Pb}) = (16.01 \pm 0.84) \text{ MeV} .$$

Values of e/mip can be derived from the values of ϵ_{vis} , and we obtain $(e/mip)_{\text{Fe}} = 0.82 \pm 0.02$ at $\tau = 1.99$. In the same way we obtain $(e/mip)_{\text{Pb}} = 0.76 \pm 0.04$ at $\tau = 1.96$. These results can be compared with i) a Si/Cu calorimeter giving about $(e/mip)_{\text{Cu}} = 0.85$ [8] at $\tau = 1.05$; ii) a Si/Pb calorimeter giving about $(e/mip)_{\text{Pb}} = 0.71$ [8] at $\tau = 1.07$. The two sets of experimental data are in agreement and show that $(e/mip)_{\text{Fe}}$ is larger than $(e/mip)_{\text{Pb}}$ by about (8–14%).

At 4 GeV, the visible energy in a Si/Pb calorimeter (at $\tau = 1.96$) has been measured with additional G10 absorbers, 1.5 mm thick, located both at the front and at the rear of the detector planes (a total of 4.2 mm of G10, including the support of the mosaic). A reduction of the visible energy has been found: $[\epsilon_{\text{vis}} - \epsilon_{\text{vis}}(\text{Pb})]/\epsilon_{\text{vis}}(\text{Pb}) = -(20.1 \pm 2.0)\%$, where $\epsilon_{\text{vis}}(\text{Pb})$ is the visible energy with no G10 (as given above). The measurements show that in the case of a Si/Pb calorimeter, the local hardening effect is operating to the same extent as for a silicon calorimeter with W or U as the passive medium [2]. Thus the compensation condition can be achieved by thin G10 layers (with a thickness less than 5 mm) inserted mainly at the rear of the silicon detectors.

Furthermore, the local hardening effect can be exploited to reduce also the electromagnetic Si/Fe calorimeter response, albeit to a lower extent (as mentioned before). The measured visible energy in the Si/Fe calorimeter with $\tau = 1.99$ and 10 mm of G10 (in addition to the 1.2 mm of the mosaic support), for incoming electrons with an energy of 4 GeV, is $\epsilon(1) = (5.65 \pm 0.14) \text{ MeV}$. Thus the visible-energy reduction is $[\epsilon(1) - \epsilon_{\text{vis}}(\text{Fe})]/\epsilon_{\text{vis}}(\text{Fe}) = -(16.5 \pm 1.6)\%$, where $\epsilon_{\text{vis}}(\text{Fe})$ is the visible energy with no G10. The $(e/mip)_{\text{Fe}}$ ratio is ≈ 0.74 .

Brau's Monte Carlo results [5] (where only a 1.0 mm G10 layer has been considered) show that the compensation condition can be achieved if the h/mip ratio is increased by about 9% when 10 mm

G10 plates are used. A hadronic sampling Si/Fe hadron calorimeter requires at least eight to ten samplings per interaction length, and six interaction lengths for full longitudinal shower containment for hadrons with an energy of 10 GeV. Thus the amount of G10 material in which the evaporated neutrons (and some of the quasi-direct neutrons) can generate recoiling protons is not negligible. When these further interactions are taken into account, the h/mip increase is estimated to amount to 6–9%. The precise value is related to the calorimeter operating condition (namely, the integration time of the readout electronics) and the calorimeter structure (namely, the number of samplings per interaction length).

From this interplay, the result of our measurements indicates that the compensation condition can be achieved even in Si/Fe calorimeters with G10 plates inserted, when the proper calorimeter structure and readout electronics are used.

6. CONCLUSIONS

We find experimental evidence for a filtering effect on the soft-electron component in electromagnetic showers when combinations of low-Z and high-Z materials are used as absorbers.

In order to realize the so-called compensation condition, the response to the electromagnetic component of the shower can be increased or decreased. The filtering effect can be fully exploited to reduce the electromagnetic calorimeter response, which makes it possible to achieve the compensation condition in a Si/(Fe + Pb) calorimeter with an effective interaction length almost equal to that of Fe. In fact, this is realized by building a sampling calorimeter made of a very thick, low-Z (Fe) absorber and a thin, high-Z (Pb) absorber. The action of Fe on Pb, by modifying the critical energy during the electromagnetic shower development, leads to a yield of soft electrons (and very few photons) that are easily stopped in subsequent absorber layers and/or absorbed by the G10 plates.

In Si/Pb calorimeters, there is evidence of a local hardening of the electromagnetic showers when low-Z G10 absorbers are located near the silicon detectors. This effect reduces the visible energy, as has been observed in Si/W and Si/U electromagnetic calorimeters.

In Si/Fe calorimeters, the local hardening effect can be exploited when the adequate calorimeter structure and readout electronics are used.

Acknowledgements

We wish to thank I. Fedder for his help. The support of the CERN PS Division, and particularly the help of K. Bätzner, are gratefully acknowledged.

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Figure captions

- Fig. 1 $\epsilon_{\text{vis}}\tau$ as a function of the sampling frequency τ for incoming electrons of 4 GeV for Si/Fe, Si/Pb, and various configurations with Fe ($1.99X_0$ thick) and Pb as absorbers: $\square$ PbFePb-Si-PbFePb, $\triangle$ FePb-Si-FePb, $\circ$ PbFe-Si-PbFe, $\times$ Si-Pb, and $\bullet$ Si-Fe.
- Fig. 2 e/mip as a function of the Pb fraction f in the passive absorber [$f \equiv L_{\text{Pb}}/(L_{\text{Pb}} + L_{\text{Fe}})$]; L_i is the thickness of absorber i for various calorimeter configurations (Fe is $1.99X_0$ thick) and for 4 GeV incoming electron energy: $\bullet$ PbFe-Si-PbFe, $\times$ FePb-Si-FePb, and $\circ$ PbFePb-Si-PbFePb.
- Fig. 3 ϵ_{vis} obtained from $(h/\text{mip})E_s$ (continuous line), given by the Monte Carlo calculation when $e/\pi = 1$, the calibration being simply obtained by the response to a minimum-ionizing particle, compared with ϵ_{vis} measured for the PbFe-Si-PbFe configuration (dashed line). The exact fraction of Pb ($\sim 25\%$) needed to achieve the compensation is indicated at the crossing point of the two lines. The incoming electron energy is 4 GeV and the thickness of Fe is $1.99X_0$.
- Fig. 4 Reduction of the electromagnetic shower energy due to the local hardening effect, $\Delta\epsilon_{\text{vis}}/\epsilon_{\text{vis}}$, as a function of the Pb fraction in the absorber at 4 GeV for the PbFe-Si-PbFe configuration when low-Z G10 absorbers, 5 or 10 mm thick, are inserted at the rear of the Si detectors (i.e. in front of the high-Z Pb absorbers).
- Fig. 5 The visible (electromagnetic) energy ϵ_{vis} measured for an Fe absorber $1.99X_0$ ($X_0 = 1.76$ cm for Fe) as a function of the incident energy (E in GeV). The calorimeter response is linear: $\epsilon_{\text{vis}} = (-0.33 \pm 0.34) + (1.51 \pm 0.12)E(\text{GeV})$ [MeV].
- Fig. 6 The visible (electromagnetic) energy ϵ_{vis} measured for a Pb absorber $3.39X_0$ thick ($X_0 = 0.56$ cm for Pb) as a function of the incident energy (E in GeV). The calorimeter response is linear: $\epsilon_{\text{vis}} = (-0.36 \pm 0.50) + (2.20 \pm 0.12)E(\text{GeV})$ [MeV].

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6