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INVESTIGATION OF THE LOCAL HARDENING EFFECT PRODUCED BY VARIOUS LOW-Z MATERIALS IN A Si/(Fe,Pb) ELECTROMAGNETIC CALORIMETER

SICAPO Collaboration

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Abstract

The condition for obtaining the linear response of a calorimeter to hadronic showers and an energy resolution that improves as the incident energy increases is the equalization of the electromagnetic (e) and the hadronic (π) signals. This equalization is obtained by exploiting a local hardening effect realized through the insertion of low-Z thin plates between the high-Z absorbers and the active material in a hadronic calorimeter with silicon readout. This effect, which allows the reduction of the calorimeter response to the electromagnetic component of the incoming hadronic showers, has been investigated for different low-Z materials. The relevance of some aspects of this study to the radiation hardness of the calorimeters is also addressed.

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1. INTRODUCTION

Hadron calorimeters will constitute the core element of the central detection systems operating in the experiments to be performed at the Large Hadron Collider (LHC) and at the Superconducting Super Collider (SSC).

Reasons have been given previously [1,2] is support of the idea that a sampling hadron calorimeter with silicon as the active medium is one of the best candidates to meet the severe requirements imposed by the high luminosity, high multiplicities, and large variety of physics phenomena encountered at these machines. These requirements are compact and flexible construction, fine granularity, fast charge collection, easy calibration, and good radiation hardness. The use of silicon detectors also permits the achievement of the compensation condition ($e/\pi = 1$) that makes it possible to reach the energy resolution requested by the physics aimed at by the experiments at the next generation of colliders. The performances of hadron calorimeters is determined by their relative response to the electromagnetic (e) and hadronic (π) shower, the e/π signal ratio, defined as

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

where mip is the energy deposited in the sensitive part of the calorimeter by a minimum-ionizing particle $h(1 - f_{\mathrm{em}})$ is the visible hadronic energy (i.e. the energy deposited in the detector readouts by the purely hadronic component of the shower, see refs. [1] and [2] and references therein); f_{em} varies with energy and is the average fraction of the converted electromagnetic energy resulting from the photon decays of π^0 and η particles produced during the hadron cascade. In the electromagnetic cascading, all the energy resulting from the interaction of the particles of the shower with the medium is visible. In the hadronic interactions of a cascade, a sizeable amount of the available energy is converted into excitation or breakup of the absorber nuclei, of which only a fraction results in visible energy (ϵ_{vis}). The energy resolution can generally be written as

$$\sigma/E = C/\sqrt{E} + \phi[(e/\pi) - 1] , \tag{2}$$

where $C = (\sigma^2_{\mathrm{intr}} + \sigma^2_{\mathrm{samp}})^{1/2}$ contains the contribution from the intrinsic fluctuations due to nuclear binding energy losses (σ_{intr}) and that from the sampling fluctuations (σ_{samp}). The function ϕ vanishes only if $e/\pi = 1$. In order to obtain a linear response of a calorimeter to hadronic showers and an energy resolution that improves as the incident energy increases, i.e. $\phi = 0$ in Eq. (2), it is then necessary to equalize the calorimeter response to the electromagnetic and the hadronic showers.

This equalization can be performed in calorimeters with silicon readout through a local hardening effect. This effect can be exploited in order to reduce the visible electromagnetic energy [3,4] beyond what is normally expected from the energy sharing. The local hardening effect is realized via the insertion, between the silicon detectors and the absorber planes, of low-Z absorber (G10) planes, which absorb the flux of backward-going electrons created by multiple scattering. This leads to a decrease of the visible electromagnetic energy and hence to the compensation.

Another approach to the achievement of the compensation condition has appeared [5,6]. The use of a combination of low-Z and high-Z materials as absorber allows the transformation of the electron energy distribution of the incident showers in two media with different critical energies. This results in a filtering effect [5,6]. The action of the low-Z on the high-Z material, by modifying the critical energy during the electromagnetic shower development, leads to a yield of soft electrons (and very few photons).

The local hardening and filtering effects can be combined. Indeed, the soft incoming electromagnetic shower component, created by the filtering effect and the flux of backward-going electrons (resulting from multiple scattering in the high-Z absorber), are absorbed by thin low-Z (G10 for instance) plates inserted between the active and passive media, and again a decrease of the electromagnetic visible energy is produced.

The aim of the present paper is to discuss the way this equalization, i.e. the compensation condition ($e/\pi = 1$), is achieved. A study of the local hardening effect produced by different low-Z materials is reported in this paper. The intense radiation environment created at the next generation of colliders could have some impact on the choice of the low-Z material used to exploit the local hardening effect. In that respect, a low-Z material, such as polyethylene, could serve as a neutron moderator. This attractive possibility is also discussed in the present paper.

2. THE LOCAL HARDENING EFFECT

The ratio e/mip ratio measures the energy deposited in the sensitive part of the calorimeter by electron and photon showers relative to minimum-ionizing particles and is defined as

$$e/\mathrm{mip} = \epsilon_{\mathrm{vis}}(e)/E_{\mathrm{s}} \, ,$$

where $\epsilon_{\mathrm{vis}}(e)$ is the visible (electromagnetic) energy measured in the calorimeter and E_{s} is the energy shared by the minimum-ionizing particles in the silicon detectors and is given by

$$E_{\mathrm{s}} = (\mathrm{d}E/\mathrm{d}x)_{\mathrm{Si}} X_{\mathrm{Si}} E / [(\mathrm{d}E/\mathrm{d}x)_{\mathrm{Si}} L_{\mathrm{Si}} + \sum_i (\mathrm{d}E/\mathrm{d}x)_i L_i] \, ,$$

where X_{Si}, L_{Si}, L_i, $(\mathrm{d}E/\mathrm{d}x)_i$, and E are 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.

Experimental evidence has been found [3,4] for a local hardening effect obtained by inserting thin plates of low-Z absorber (G10) next to the silicon readout detectors. The suppression of the electromagnetic response of the calorimeter can occur owing to multiple scattering. In electromagnetic cascade showers, the energy is propagated, both laterally and longitudinally, by an increasing number of electrons and photons of diminishing energy. It is well-established that a considerable fraction of the energy deposition in the calorimeter is done through low-energy particles [3,4]. As an indication, Monte Carlo simulations show that in the case of uranium, for instance, particles with an energy below 1 MeV account for about 40% of the total energy deposition. A large fraction of the initial electron energy goes into the production of low-energy photons during the shower development. The interaction between these soft photons and matter is dominated by Compton scattering and the photoelectric effect for energies up to 5 MeV. The contribution of the Compton cross-section to the total cross-section for photon interactions in a given material is proportional to its Z number (accounting for the Z electrons per atom). The dependence of the photoelectric cross-section on the atomic number Z of the material varies somewhat with the energy of the photon; however at MeV energies (which is our case), this dependence is approximately Z^4–Z^5. Therefore, the interaction cross-section of these soft photons is much larger in the high-Z absorber than in the low-Z active medium. The soft photons from the shower interact almost exclusively in the absorber and most of them will transfer their energy to the electrons of the absorber via the Compton and photoelectric effects. Regarding the Compton effect, only a part of the energy is transferred to the recoil electron (absorption cross-section). Concerning the photoelectric effect, the energy of the soft photons is totally transferred to the electrons of the absorber.

As a consequence, low-energy photons from the electromagnetic shower development may convert into electrons sufficiently close to the surface of the absorber plate for them to escape usually to contribute to the measured signal. These low-energy electrons may be multiply-scattered. In a high-Z material, the low-energy electrons form larger angles α with respect to the shower axis than in a low-Z material:

$$\langle \cos\ \alpha \rangle = \cos(21\ \mathrm{MeV}/\epsilon\pi)\ ,$$

where $\epsilon\ =\ B(ZX_0/A)^a$ is the critical energy [7] for a material (A, Z) (A is the atomic mass, $B = 2.66$, $a = 1.11$, and the radiation length $X_0\ \approx\ 180\ (A/Z^2)$ [g/cm^2] [8]).

The number of large-angle electrons (decreasing as ϵ^2) is large in high-Z material and small in low-Z material. Multiple scattering increases the pathlength of the electrons: their path-length d becomes $d'\ \equiv\ d/\langle\cos\ \alpha\rangle$. Therefore the e/mip value for an absorber i behaves as

$$e/\mathrm{mip}\ \approx\ (d'_{\mathrm{Si}}/d_{\mathrm{Si}})/(d'_{\mathrm{i}}/d_{\mathrm{i}})\ , \tag{3}$$

neglecting any multiple scattering for a minimum ionizing particle and the energy loss in the active medium of the calorimeter. It shows that e/mip clearly depends on the ratio d'/d and, since $d'/d > 1$ and $d'_{\mathrm{Si}}/d_{\mathrm{Si}} \approx 1$, one has $e/\mathrm{mip} < 1$.

Multiple scattering creates a flux of backward-going electrons in the absorber. These soft electrons can be absorbed by the G10 plates inserted between the active and the absorber planes and which are, therefore, responsible for the decrease of the visible energy: the local hardening effect [3,4]. This effect has been observed from a systematic investigation of the visible energy (ϵ_{vis}) response for electromagnetic showers in Si/U and Si/W electromagnetic calorimeters [3,4]. This study, carried out for various incoming electron energies, has shown, for instance, a reduction (29%) of the visible electromagnetic energy in the case of the 5.0 mm G10 absorber located at the rear (only) of the detectors, leading to a reduction of about 20% of the ratio of the electromagnetic to the non-electromagnetic shower component.

For a given absorber σ_{samp} can be easily modified and eventually decreased by changing the frequency of the sampling. The resolution σ_{intr} is sensitive to the number of neutrons released by the absorber per GeV of incident energy and can be minimized by an adequate choice of the absorber. For instance, $\sigma_{\mathrm{intr}}/E = 45\%/\sqrt{E}$ for a uranium absorber and $18\%/\sqrt{E}$ for a Fe absorber.

The physics goals and the processes that limit the effective energy resolution fix the required calorimeter energy resolution at $\sigma/E \approx\ 50\%/\sqrt{E}$ [1]. Therefore, aiming at this energy resolution leads to the concept of a calorimeter with a Fe dominated absorber and a small fraction of high-Z metal. This creates a situation where the compensation condition has to be achieved in a silicon calorimeter with a combination of low-Z (Fe) and high-Z (chosen as Pb) as the passive medium.

3. LOCAL HARDENING EFFECT IN Si/(Fe,Pb) AND Si/Fe ELECTROMAGNETIC CALORIMETERS

Data have been taken with a silicon sampling electromagnetic calorimeter installed in the t_9 beam-line at the CERN Proton Synchrotron (PS). The energy of the incoming electrons was 4 GeV.

The absorbers consisted of Pb and Fe plates, whose total thickness could be varied. The total calorimeter depth was varying from a minimum of 20 to a maximum of 50 radiation lengths. The absorber plates were interspaced with silicon readout mosaics. The readout planes (of about 250 cm^2 active area) were made of a mosaic of trapezoidal silicon detectors [9]. A trapezoidal detector had an area of about 28 cm^2 and was 400 μm thick. The detectors were operated at a depleted layer width of 200 μm. The mosaic planes were on a G10 support 0.2 and 1.0 mm thick (front and rear side 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, allowed fast electronics (about 100 base-time signals) with a wide dynamical range (five decades) to be employed. A gas Cherenkov counter filled with helium at 1.4×10^5 Pa, was used to select electrons. A beam scanner consisting of a scintillator counter of 0.5×0.5 cm^2 area ensured that only those electrons impinging on the middle of the calorimeter triggered. The absolute energy calibration had been performed following two independent approaches: i) by ^{241}Am α sources (5.48 MeV) [3,4]; ii) by minimum-ionizing particles (mip) which give a well-known energy-loss distribution in the silicon readout detectors. The two methods agree well with each other and the error on the absolute energy scale is about 2%. Our measured ϵ_{vis} had to be corrected for the energy losses in the dead zones between detectors in the mosaics. For both 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 [10].

Figure 1 shows the e/mip ratio as a function of the Pb fraction f in the passive absorber [$\mathrm{f} \equiv L_{\mathrm{Pb}}/(L_{\mathrm{Pb}} + L_{\mathrm{Fe}})$] for various calorimeter configurations ($L_{\mathrm{Fe}} = 1.99X_0$). For the configurations, FePb–Si–FePb and PbFePb–Si–PbFePb, where the forward-generated electrons in Pb can enter the silicon detectors directly, there is an increase of the value of the ratio e/mip up to $f \approx (5\text{–}8)\%$. For the PbFe–Si–PbFe configuration, where the forward-generated electrons in Pb now enter the Fe absorber, e/mip is steadily decreasing (the so-called filtering effect [5]) and equal to 0.60 ± 0.02 at $f = 0.36$.

However, in the PbFe–Si–PbFe configuration the backward-going electrons can reach the detectors since they are produced at the surface of the Pb close to the detector. Therefore, it is necessary to insert G10 plates at the rear of the silicon detectors. Figure 2 shows the reduction of the visible energy ($\Delta\epsilon_{\mathrm{vis}}/\epsilon_{\mathrm{vis}}$) for two thicknesses (5 and 10 mm) of G10 inserted between the Pb and the rear of the silicon detectors.

Considering now an FePb–Si–PbFe configuration where each Pb absorber plate is 6 mm thick ($L_{\mathrm{Fe}} = 1.99X_0$), the fraction of Pb in the absorber is $f = 0.26$ and, from fig. 1, a ratio e/mip ≈ 0.8 is then expected. If G10 plates 5.0 mm thick are inserted in the configuration [i.e. FePb–G10(5mm)–Si–G10(5 mm)–PbFe], the reduction of the electromagnetic shower due to the local hardening effect $\Delta\epsilon_{\mathrm{vis}}/\epsilon_{\mathrm{vis}} = (24.0 \pm 1.6)\%$ and is independent of the thickness of the Pb as can be observed in fig. 3. Therefore, fig. 1 indicates a ratio e/mip ≈ 0.6 (decreased by 24%), after the insertion of the 5.0 mm thick G10 plates in the configuration is achieved. The fact that $\Delta\epsilon_{\mathrm{vis}}/\epsilon_{\mathrm{vis}}$ is independent of the

Pb thickness (fig. 3) means that this effect, in this particular configuration (FePb–Si–PbFe), is due to soft electrons and photons generated at the surface of the Pb.

Data have been taken with the same calorimeter but with an FeAl–Si–AlFe configuration. The results are reported in table 1, where it can be seen that the $\Delta\epsilon_{\mathrm{vis}}/\epsilon_{\mathrm{vis}}$ ratio is increased by a factor of about two when the thickness of the Al is doubled in the calorimeter configuration. This effect on the ratio is larger when the Al is put in front of the silicon detectors compared with the case where it is put behind them. This trend is opposite to that observed in the case of a high-Z absorber.

4. LOCAL HARDENING EFFECT DUE TO POLYETHYLENE AND NEUTRON MODERATION

The ratio $\Delta\epsilon_{\mathrm{vis}}/\epsilon_{\mathrm{vis}}$ has been measured as a function of the Pb thickness in a sampler (made of a combination of Fe and Pb) in three cases, corresponding to the insertion of 5 mm thick layers of Al, polyethylene, and G10 in front and at the rear of the silicon mosaics in a FePb–Si–PbFe configuration. The results are shown in table 2. In the three cases $\Delta\epsilon_{\mathrm{vis}}/\epsilon_{\mathrm{vis}}$ is seen to be independent of the Pb thickness and means that the local hardening effect is due to soft electrons and photons generated at the surface of the Pb (see also ref. [11]).

These values of $\Delta\epsilon_{\mathrm{vis}}/\epsilon_{\mathrm{vis}}$ lead to reduced e/mip ratios and the possibility of tuning the e/π ratio. Direct evidence of the effectiveness of the local hardening effect in modifying the response of a hadronic calorimeter to the incoming showers, for silicon readout and uranium as absorber has recently been obtained [12]. In the case of a Si/U hadron calorimeter a ratio $e/\pi = 1$ is obtained, resulting from the insertion of G10 plates (1.2 ± 0.2) mm thick in front and at the rear of the silicon detectors, instead of the value $e/\pi > 1$ measured when a small amount of low-Z absorber (G10) is employed.

The measurement of the reduction of the electromagnetic shower energy due to the local hardening effect for several thicknesses of polyethylene inserted in the calorimeter configuration is shown in fig. 4 as a function of the Pb thickness in a sampler. Comparing with a similar study made previously [3,4,11] where various thicknesses of G10 were used, one can conclude that the insertion of polyethylene layers in front and at the rear of the silicon mosaics leads to a level of reduction of the visible electromagnetic energy $\Delta\epsilon_{\mathrm{vis}}/\epsilon_{\mathrm{vis}}$ similar to that obtained with G10. The next generation of colliders will create environments of high-level radiations challenging the survival of the calorimeters operating in the experiments. The neutrons, with fluences estimated to reach up to 10^{12} cm^{-2} a^{-1} are at the core of the problem. The large cross-section of neutrons on hydrogen nuclei suggests introducing hydrogeneous material in the silicon calorimeter in order to moderate this effect. Polyethylene, a hydrogen-rich material, presents the advantage that, in addition to providing the means of achieving the compensation condition, it can play the role of neutron moderator in a hadron calorimeter. Preliminary results, have been reported involving the exposure to very intense beams at the CERN PS, of Na, In, and Rho foils, with and without polyethylene foils in a dump calorimeter [13]. These results give an indication that the low-energy neutron flux should be reduced by as much as an order of magnitude with polyethylene foils with a thickness of the order of 1 cm.

5. CONCLUSION

The local hardening effect has been measured for different thin low-Z materials plates inserted in a calorimeter with silicon readout, with combinations of Fe and Pb as absorbers. The consequence of this effect is a reduction of the response of the calorimeter to the electromagnetic part of the incoming hadron showers beyond the amount normally expected from energy sharing. Therefore the tuning of the e/π ratio becomes possible.

The results of this study show that the insertion of polyethylene layers in front and at the rear of the silicon mosaics leads to a level of reduction of the visible electromagnetic energy $\Delta\epsilon_{\mathrm{vis}}/\epsilon_{\mathrm{vis}}$ similar to that obtained for G10. Therefore polyethylene can be used instead of G10 to achieve the compensation condition ($e/\pi = 1$). However, the possible use of polyethylene presents the advantage, over G10, that it plays the role of a neutron moderator, as indicated by recent activation studies [13], and may then contribute to reinforcing the calorimeter radiation hardness.

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Table 1

The ratio $\Delta\epsilon_{vis}/\epsilon_{vis}$ for 4 GeV incoming electrons
as a function of the Al thickness
in the FeAl(1)–Si–Al(2)Fe configuration

Al(1) thickness (mm)	Al(2) thickness (mm)	$\Delta\epsilon_{vis}/\epsilon_{vis}$
3.0	3.0	5.3 ± 3.4
5.0	5.0	10.1 ± 3.4
0.0	10.0	8.2 ± 3.4
10.0	0.0	11.4 ± 3.4
0.0	5.0	4.3 ± 3.4
5.0	0.0	7.7 ± 3.4

Table 2

The ratio $R \equiv \Delta\epsilon_{vis}/\epsilon_{vis}$ for 4 GeV incoming electrons as a function of the Pb thickness in the FePb–Si–PbFe configuration for Al, G10, and polyethylene plates, 10 mm thick inserted at the back of the silicon detectors planes. The Pb plates in a sampling are of the same thickness.

Pb thickness (mm)	R(%) for:		
	Al	G10	Polyethylene
1.0	19.0 ± 2.7	15.2 ± 2.7	15.4 ± 2.7
1.5	19.7 ± 3.1	14.5 ± 3.1	19.3 ± 3.1
2.0	21.2 ± 3.8	11.7 ± 3.8	16.1 ± 3.8

Figure captions

Fig. 1: e/mip as a function of the Pb fraction f in the passive absorber ($f \equiv L_{\rm Pb}/[L_{\rm Pb} + L_{\rm Fe}]$); L_i is the thickness of the absorber i for various calorimeter configurations (Fe is $1.99X_0$ thick) and for 4 GeV incoming electron energy: (•) PbFe–Si–PbFe, (×) FePb–Si–FePb, and (o) PbFePb–Si–PbFePb.

Fig. 2: The reduction of the visible energy ($\Delta\epsilon_{\rm vis}/\epsilon_{\rm vis}$) as a function of the Pb fraction in the absorber for 4 GeV incoming electrons for a PbFe–Si–PbFe configuration when G10 absorbers 5 and 10 mm thick are inserted between the Pb and the rear of the silicon detectors.

Fig. 3: Reduction of the visible energy sensed by the calorimeter for 4 GeV incoming electrons, $\Delta\epsilon_{\rm vis}/\epsilon_{\rm vis}$, as a function of the Pb thickness in the absorber. The line is to guide the eye.

Fig. 4: Reduction of the visible energy sensed by the calorimeter for 4 GeV incoming electrons, $\Delta\epsilon_{\rm vis}/\epsilon_{\rm vis}$, as a function of the Pb thickness in the absorber for various thicknesses (in mm) of polyethylene layers inserted in front/at the rear of the silicon mosaics in a FePb–Si–PbFe configuration.

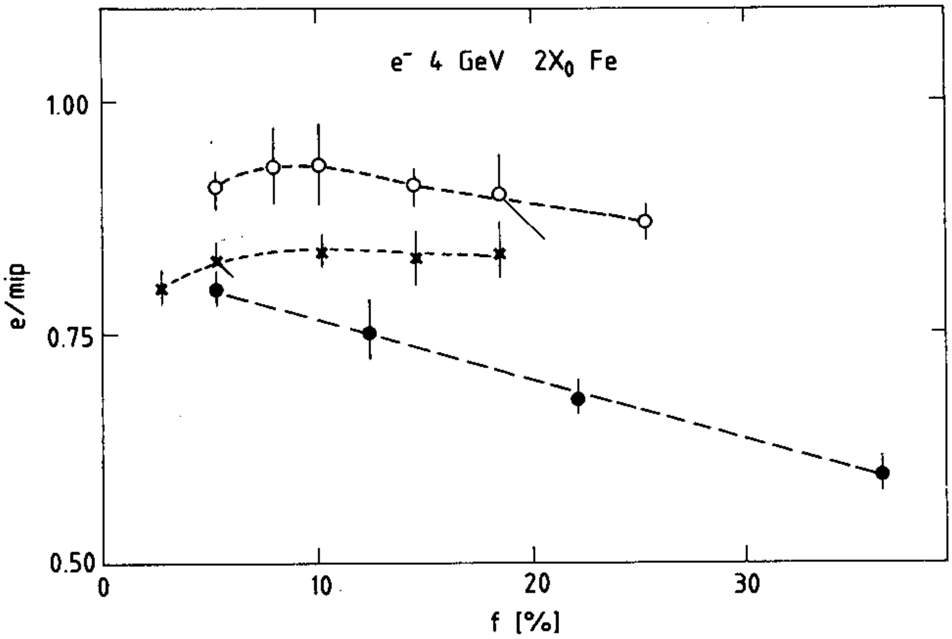
e⁻ 4 GeV 2X₀ Fe
e/mip
1.00
0.75
0.50
0
10
20
30
f [%]

Fig. 1

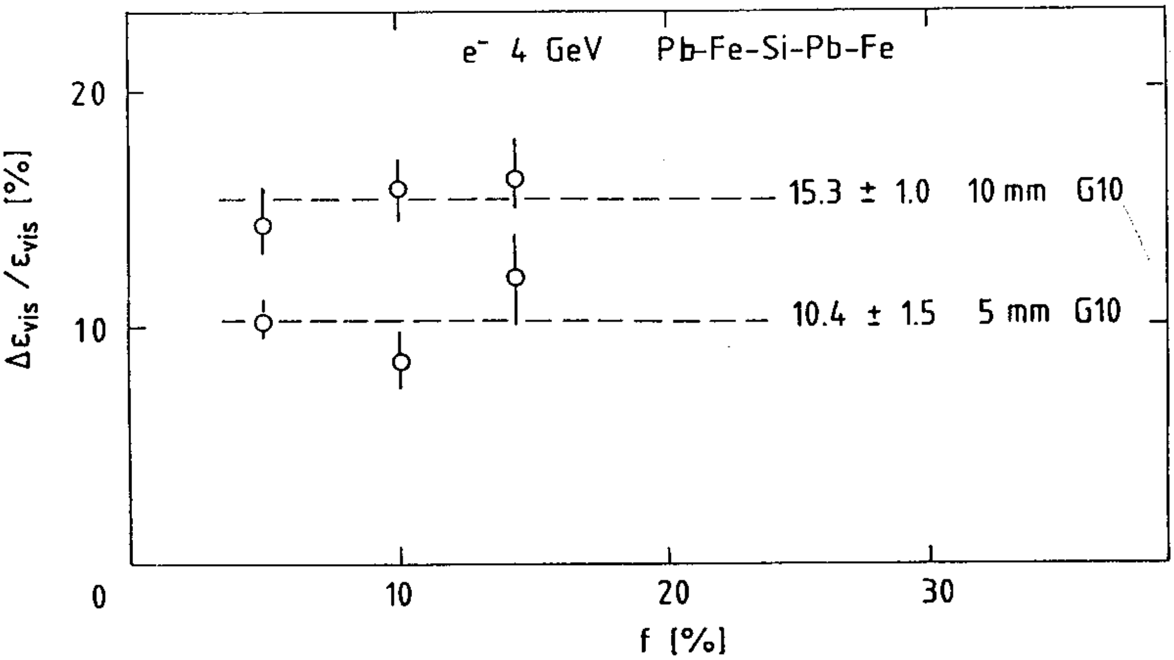
e⁻ 4 GeV Pb-Fe-Si-Pb-Fe
Δε_vis / ε_vis [%]
20
10
0
10
20
30
f [%]
15.3 ± 1.0 10 mm G10
10.4 ± 1.5 5 mm G10

Fig. 2

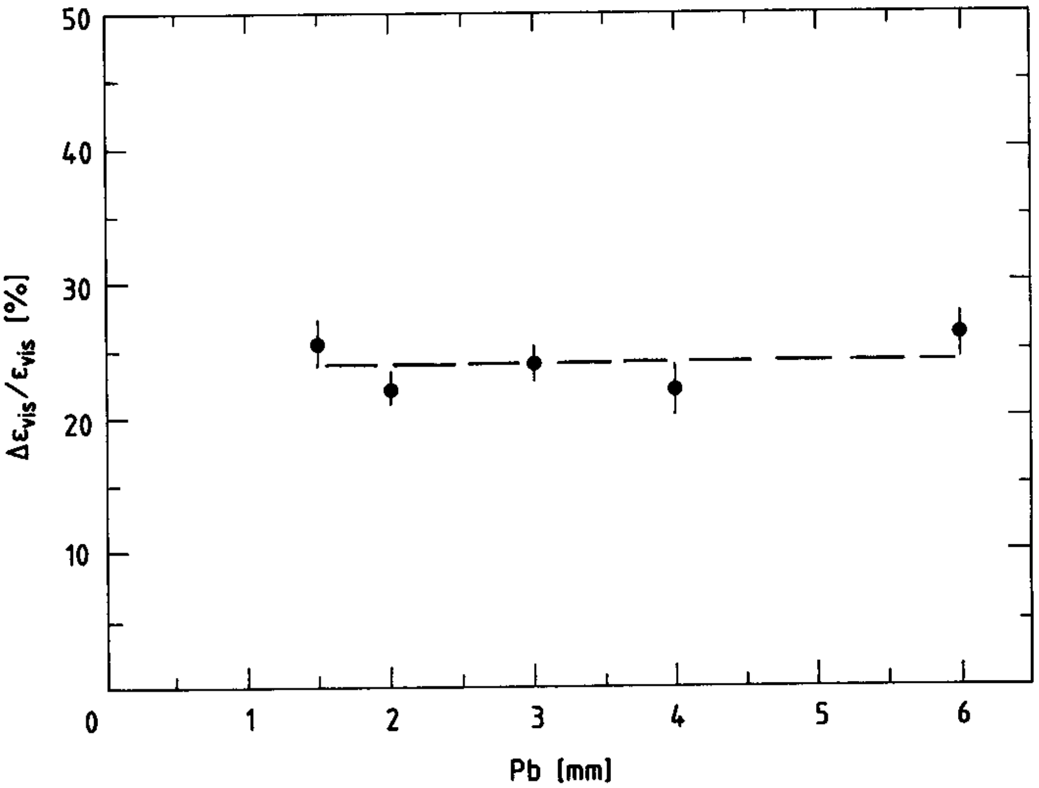

Fig. 3

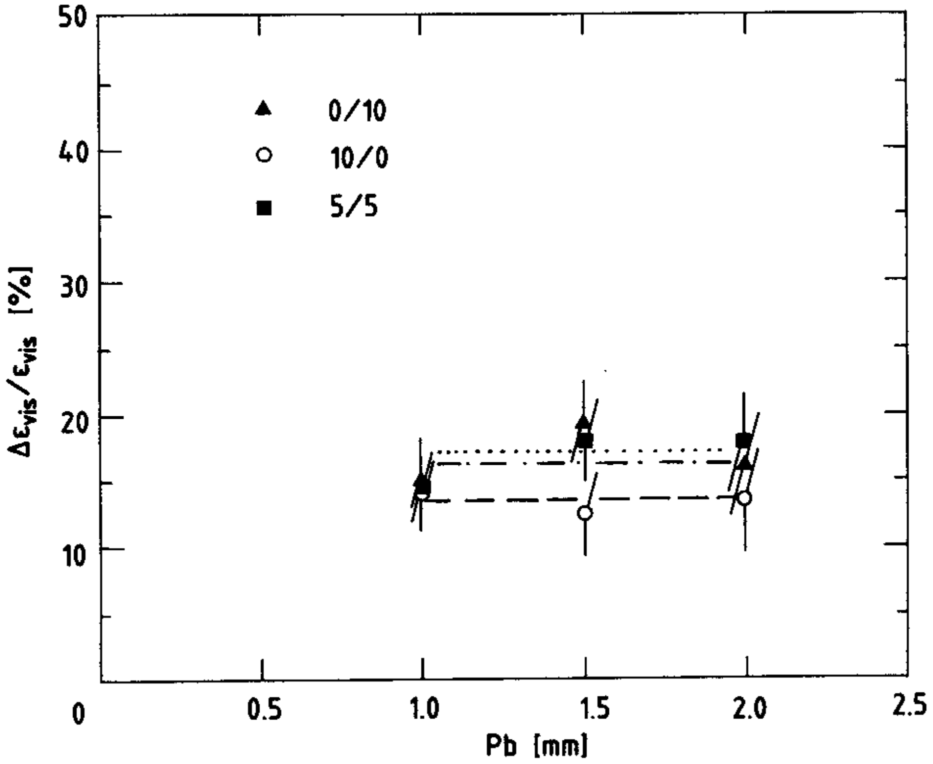

Fig. 4

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