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**THE LOCAL HARDENING EFFECT ON ELECTROMAGNETIC SHOWERS:
A WAY FOR SIGNAL EQUALIZATION IN SI/HIGH-Z HADRON CALORIMETERS**

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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 between the electromagnetic and the hadronic signals. This equalization is obtained, within a new approach, by exploiting a local hardening effect that is realized by inserting low- Z absorbers next to the silicon readout detectors. In this way, the calorimeter response to the electromagnetic component of the hadronic shower is reduced. A systematic investigation of the visible energy response for electromagnetic showers in Si/U and Si/W calorimeters has been carried out for incoming electron energies of 2, 4, and 6 GeV. The insertion of low- Z material (G10 plates) in front or at the rear of the silicon detectors allows a fine tuning of the calorimeter response.

1. INTRODUCTION

For the last few years the SICAPO Collaboration (Florence, Hamburg, McGill, Messina, Milan, Oregon, Tel Aviv, Tennessee, Trieste, Turin) has been involved in the study of the compensation properties of hadron calorimeters to be used in experiments at the next generation of colliders. Calorimeters are instrumented blocks of matter in which the energy of a particle is degraded to the level of ionizations and excitations that are detectable by the readout media. Independent of their structure, the calorimeters must be of sufficient thickness to allow the particle to deposit all its energy inside the detector volume, in the subsequent cascade of increasingly lower-energy particles. Calorimeters allow the measurement of the energy, position, and angle of the incident particle. Their different response to electrons, muons, and hadrons can be exploited for particle identification.

Future experiments at colliding-beam machines, in particular at the next generation of hadron colliders [the Large Hadron Collider (LHC) at CERN and the Superconducting Super Collider (SSC) in the USA], will require severe constraints on the performance of the calorimeter system [1]: high granularity in order to provide precise measurements of angles and to allow the separation of very close jets; compactness and flexibility in order to accommodate the relatively small space made available in the intersection regions by small crossing angles. Calorimeters must have also good electromagnetic and hadronic energy resolutions. In practice, sampling hadron calorimeters, where the degraded energy is measured in a number of active layers interspersed with massive absorber, will be used for these future projects. Contrary to the electromagnetic cascading, which is fully described [2] by quantum electrodynamics (QED) and depends essentially on the density of electrons in the absorber medium, the hadronic cascading is propagated by a variety of complex hadronic processes [3]. Decays of hadronic resonances created during the degradation of the energy of the incident hadrons, and charge-exchange reactions in these processes, yield an electromagnetic component for any hadronic shower; this component is largely determined by the production of π and μ in the first interaction, and therefore event-by-event fluctuations are important. In the hadronic interactions of a cascade, a sizeable amount of the available energy is converted into excitation or break-up of the absorber nuclei, of which only a fraction would result in visible energy. Therefore the signal per unit of incident energy will be different for electromagnetic and hadronic cascades. The performance of hadron calorimeters is determined by the relative response to the electromagnetic and non-electromagnetic shower component, the e/h signal ratio. Equalizing the response of the calorimeter to electrons and hadrons ($e/h = 1$, the compensation condition) is the condition for reaching optimal performances of the calorimeter. It has been shown [4, 5] that the e/h signal ratio is in fact determined by the processes that occur at the nuclear and atomic levels during the last stages of shower development. In hadron calorimeters employing hydrogenous material as active devices, the compensation condition can be achieved by increasing the relative contribution of the pure hadronic signal; this is obtained by neutrons—generated in the last stages of the hadronic shower development, where processes at the nuclear level occur—interacting on the protons of the readout material. The relative contribution of neutrons can be modified by varying the sampling fraction in order to achieve the compensation condition [6].

In the present letter we propose a new approach to the realization of the compensation condition, taking the point of view that it can also be reached by decreasing the response of the calorimeter to the electromagnetic shower. The requirements on the calorimetry system imposed by the future colliders can be satisfied by a sampling calorimeter using silicon detectors as the active devices and high-density absorber as the passive part [7]. Such a calorimeter was demonstrated to have a very good energy resolution and linearity for electromagnetic showers [8]. The signal equalization, which provides the condition $e/h = 1$, can be obtained with a silicon readout by tuning the calorimeter response to the electromagnetic component of the hadronic shower. For a silicon readout, this can be achieved by inserting low-Z absorber (G10 plates) in front and/or at the rear of

the silicon detectors [9, 10]. The fibre glass absorbs soft electrons, thus reducing the total energy sensed. The low-Z absorber is used to reduce the response of the electromagnetic component in a hadronic shower, whilst the pure-hadron component (mostly relativistic or quasi-relativistic), constituted from larger-range particles, is expected to be only slightly affected. Silicon, which does not contain hydrogen, has a prompt response that is limited only by the intrinsic transit time of the detector.

The present letter reports the results of a systematic study of the tuning of a Si calorimeter response to an electromagnetic shower, performed with small-area Si/W and Si/U calorimeters.

2. EXPERIMENTAL SET-UP

The calorimeter had 20 radiation lengths of uranium or tungsten as absorber, and a silicon detector (with a $5 \times 5 \text{ cm}^2$ area and about $300 \mu\text{m}$ thickness) as the active medium every two radiation lengths. These silicon detectors operate in reverse-biased mode [11]. The applied voltage assists the built-in voltage in removing free charges from the junction interface and from the region on either side of it. The created charge depletion layer, where the free carrier concentrations are lower than their thermal equilibrium values, provides the conditions for counter operation. The holes and electrons, which are created subsequent to the energy-loss process, migrate towards the electrodes. In the present experiment, the detectors were operated not fully depleted, with a depletion depth of $200 \mu\text{m}$.

A serial coupling (along the beam direction) of five successive silicon devices is being used to reduce the number of electronics channels and the overall detector capacitance [10].

A charge-sensitive amplifier was designed to give a linear response (dynamic range of 3.5 decades) for energies up to 80–90 MeV. The rise-time and fall-time were 25 ns and 60 ns, respectively. The standard deviation of the Gaussian noise distribution (laboratory test) was about 15 keV for an input capacitance of 280 pF (the capacitance expected for five detectors, depleted at $200 \mu\text{m}$ and coupled in series, taking into account the stray capacitance) [10].

Each of the two readout units (one for the first and one for the second 10 interaction lengths) was individually read out by its own ADC channel (LeCroy 2249A). An on-line sum, read out by a separate ADC channel, was also performed, thus measuring directly the overall energy response and resolution of the calorimeter in the various operating conditions.

The experiment was performed in the t_9 beam at the CERN Proton Synchrotron (PS), with incoming electrons of 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. In this way, the electromagnetic shower generated by the triggered electrons is contained laterally up to 2.5 and 2.6 Molière radii for tungsten and uranium, respectively.

Before and after each period of data-taking, the calorimeter was calibrated and the electronics equalized using an ^{241}Am α source (5.5 MeV). A pedestal run was taken before and after each data-taking run.

Owing to the excellent linearity of the amplifiers, the number of counts stored in the analog-to-digital converters (ADCs) and recorded on tape is a linear function of the energy deposited in each plane by the electrons of the shower. In order to retrieve the deposited energy, a pedestal value must be subtracted, and the number obtained must be multiplied by an appropriate calibration factor for the pedestal and the calibration. For the pedestal runs, a cut is imposed on the counts of each individual ADC at two standard deviations of the counts' distribution so as to ensure truly zero energy-deposition. For the runs of energy-deposition measurement, a cut is applied on the value of the ADC that measures the dE/dx at the entrance of the calorimeter, to reject events with two or more electrons arriving in coincidence; the average of the ADC counts in a run is taken for the events

passing this cut. The calibration runs are energy-deposition runs in which the deposited energy is a distribution having a known high end (the α energy from the ^{241}Am source). This high end is extracted by localizing the high-end peak through a Gaussian fit over a limited region. The calibration is constant over several days, and any calibration change would be detected since one calibration run is taken for each ADC at the beginning of the running period and one at the end. The quantity (average counts in a pedestal run) times a calibration constant is the true deposited energy in the sensitive silicon volume, in units of MeV, and it is shown as such in the figures.

3. THE LOCAL HARDENING EFFECT

Data were taken for various configurations in the calorimeter: i) a configuration where G10 plates, 0.5, 1.0, and 1.5 mm thick, were inserted both in front and at the rear of the silicon detectors; ii) a configuration where G10 plates of 0.5, 1.0, 1.5, 3.0, 4.0, and 5.0 mm thicknesses were located at the rear only; iii) a configuration where G10 plates, 5.0 mm thick, were placed between the uranium absorbers. Finally, data were taken without any G10 plates at all. Figures 1 and 2 show the mean energy sensed by the calorimeter for Si/W and Si/U, respectively, as a function of the incoming electron energy. The visible energy in the calorimeter is found to be linear as a function of the incident energy. In fig. 3, the reduction of the visible energy (from an average of measurements at incoming electron energies of 2, 4, and 6 GeV) as a function of the G10 plate thickness is shown. The systematic difference of about 1% between the reductions of the Si/U and Si/W calorimeter is accounted for by the difference in energy sharing (between Si detectors, G10 low-Z absorber, and high-Z absorbers) in the two calorimeters. The maximum reduction occurs for the maximum thickness of G10 (5.0 mm) located at the rear of the silicon detectors, where the electromagnetic response is reduced by 29%.

This reduction of the energy sensed by the silicon detectors is stronger than the reduction that is expected to be due to the addition of G10 plates, because of the sharing of energy deposition. The energy shared by the minimum ionizing particle in the silicon detectors (E_s) is given by

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

where X_{Si} , L_{Si} , L_i , $(dE/dx)_i$, 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.

The addition of 5 mm G10 plates, every two radiation lengths, accounts for a visible energy reduction of 10% for uranium absorbers in the case of minimum-ionizing and non-showering particles. The reduction obtained with the G10 located between the uranium absorbers—thus not adjacent to the silicon detector—is comparable (9.5%). In the calorimeter configurations where the silicon detectors are adjacent to the low-Z absorbers, the measurement of the visible energy is done when the back-scattered component (for G10 plates inserted at the rear of the detectors) or/and the forward component (for G10 plates inserted in the front) will be hardened locally by the low-Z absorbers. This local hardening effect increases the reduction of the visible energy beyond the reduction expected from energy sharing. The degree of hardening depends on the thickness of the low-Z absorber, allowing the fine tuning of the calorimeter response to electromagnetic showers.

Using the local hardening effect, we reduce the response of the calorimeter to an electromagnetic shower by 29% when 5 mm thick G10 plates are inserted at the rear of the silicon detectors. Even neglecting the energy deposited in the silicon detectors by recoiling protons generated by neutrons interacting in the G10 plates, the purely hadronic component of the hadronic shower (mostly not sensitive to the local hardening effect) would be reduced by about only 10% owing to the energy-sharing effect. Thus the overall e/h ratio can be reduced by about 20%. This indicates the observed range over which e/h can be tuned by this effect.

4. INTERPRETATION

The knowledge of the behaviour of electrons and photons in matter provides an understanding of these results.

In electromagnetic cascade showers, the energy is propagated both laterally and longitudinally by an increasing number of electrons and photons of diminishing energy [12]. We know that a considerable fraction of the energy deposition in the calorimeter is done through low-energy particles. For instance, EGS4 [13] Monte Carlo simulations indicate that in the case of uranium, particles with an energy below 1 MeV account for 40% of the total energy deposition. In the course of the shower development, a large fraction of the energy goes into the production of low-energy photons. The Compton scattering ($\sim Z$ of the absorber material) and the photoelectric effect ($\sim Z^5$ of the absorber material) dominate for low-energy photons (up to 5 MeV) [14]; therefore their interaction cross-section is much larger in the high- Z absorber than in the low- Z readout. As a consequence, the soft photons from the shower 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. A fraction of the low-energy photons that convert into electrons in the absorber are sufficiently close to the surface for the electrons to escape. Normally these electrons contribute to the measured signal. Low-energy electrons may be multiply scattered. The transverse dimensions of a shower, measured in radiation lengths, are much larger in high- Z material than in low- Z material, since the Molière radius scales as $r_M/X_0 = 21 \text{ MeV}/\epsilon$ [$\epsilon = B(ZX_0/A)^a$ is the critical energy [15]; X_0 is the radiation length in g/cm^2 ; A is the atomic mass; $B = 2.66$; $a = 1.11$]. Thus in a high- Z material the low-energy electrons form larger angles [$\langle \cos \alpha \rangle = \cos(21 \text{ MeV}/\epsilon\pi)$] with respect to the shower axis than in low- Z material. The number of large-angle electrons is large in high- Z material and small in low- Z material. In high- Z passive material, the multiply-scattered electrons have a path length ($d/\langle \cos \alpha \rangle$) that is relatively longer than their path length (d) in the low- Z active material. Multiple scattering can then create a flux of backward-going electrons in the absorber. Our data show that these soft electrons are absorbed by the G10 plates inserted between the active and the absorber planes, and the strongest reduction (29%) of the visible (electromagnetic) energy appears in the case of the 5.0 mm G10 absorber located at the rear of the detectors.

The use of low- Z absorbers in sampling calorimeters in order to produce a local hardening effect and control the response to electromagnetic showers is a new concept, with important consequences for calorimetry.

The energy resolution of sampling calorimeters is dominated by the sampling and intrinsic fluctuations [16] and by the value of the e/h ratio:

1) The sampling fluctuations, which are the dominant contribution to the energy resolution in electromagnetic sampling calorimeters, originate from the fact that only a small fraction of the energy is deposited in the active layers and contributes to the calorimeter signal. This source of fluctuations is dominated by the fluctuations in the total number of charged-particle tracks crossing the active layers, and its contribution is therefore proportional to the square root of the thickness of the absorber plates.

2) The intrinsic fluctuations, which constitute the main contribution to the energy resolution in hadron calorimeters, are due to the event-to-event fluctuations of the amount of energy converted into excitation or break-up of the nuclei, of which only a fraction results in detectable energy, and to decays of pions and muons into undetected neutrinos.

3) The π^0 's (mainly) and η 's produced during the degradation of the energy of the incident hadrons decay into photons and thus deposit their energy in the form of electromagnetic showers. The average fraction converted into an electromagnetic shower increases logarithmically with energy: $\langle f_{em} \rangle = 0.12 \ln E(\text{GeV})$ [17]. As a result, any hadronic shower has a purely hadronic and a purely electromagnetic component. The size of this electromagnetic component is largely determined by the

production of π^0 (and η) in the first interaction, and event-by-event fluctuations about the average value are large and non-Gaussian. The average number of π^0 's increases logarithmically with energy as $\langle n \rangle = 5 \ln E(\text{GeV}) - 4.6$ [16].

Since the nuclear effects that dominate the non-electromagnetic part of the shower have no counterpart in the electromagnetic part, the calorimeter response to the electromagnetic and non-electromagnetic parts of the hadronic shower is different, and the electromagnetic (e) to hadronic (π) signal ratio is $e/\pi \neq 1$. The signal ratio e/π being energy-dependent as a result of the logarithmic increase with energy of f_{em} , a distinction can be made between the energy-dependent e/π ratio and the (e/h) ratio, which is constant with energy and depends on the calorimeter properties only, the two ratios being related [4] by

$$e/\pi(E) = (e/h)/(1 - \langle f_{\text{em}} \rangle [1 - (e/h)]) .$$

As a consequence of points (1) to (3), the energy resolution of a calorimeter can then be written as

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

where $\sigma = (\sigma_{\text{intr}}^2 + \sigma_{\text{samp}}^2)^{1/2}$ contains the contribution from the intrinsic fluctuations due to nuclear binding energy losses (σ_{intr}) and that from the sampling fluctuations (σ_{samp}); $f(e/\pi)$ is energy-dependent as a result of the logarithmic increase of $\langle n \rangle$ with energy and is vanishing only if $e/\pi = 1$. This can be obtained when $e/h = 1$. Therefore a ratio $e/h \neq 1$ will cause the energy resolution not to depend on the incident energy as $1/\sqrt{E}$, and the calorimeter signal not to be proportional to the incident hadron energy (non-linearity) [17].

5. CONCLUSIONS

Our results indicate that an appropriate exploitation of the local hardening effect realized by introducing low-Z absorbers, located mainly at the rear of the silicon detector, may provide an adequate range of electromagnetic signal reduction, while the pure-hadron signal component (mostly relativistic or quasi-relativistic) is virtually not affected. This tuning can then provide a situation where the intrinsic responses of the calorimeter to purely electromagnetic and purely hadronic components of the showers are made equal, i.e $e/h = 1$. As a consequence, the calorimeter will have a linear response to the incident hadron energy, and an energy resolution that improves with increasing energy as $1/\sqrt{E}$. The local hardening effect that we created is, by its nature, completely different from the effect due to electromagnetic sampling inefficiencies or transition effects [18].

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Figure captions

- Fig. 1 Mean energy deposited in the Si/W calorimeter as a function of the incoming electron energy. The top points correspond to the case of no absorber in front of the detectors. The other points correspond to a configuration with G10 in front and at the rear of the detectors: (from top to bottom) 0.5, 1.0, 1.5, 3.0, 4.0, and 5.0 mm, respectively.
- Fig. 2 Mean energy deposited in the Si/U calorimeter as a function of the incoming electron energy. The top points correspond to the case of no absorber in front of the detectors. The other points correspond to a configuration with G10 in front and at the rear of the detectors: (from top to bottom) 0.5, 1.0, 1.5, 3.0, 4.0, and 5.0 mm, respectively.
- Fig. 3 Reduction of the visible (electromagnetic) energy sensed by the calorimeter ($\square$ for Si/U, and $*$ for Si/W) versus the G10 plate thickness inserted in front and at the rear of the silicon detectors.

Fig. 1

Fig. 2

Fig. 3