INVESTIGATION OF ELECTROMAGNETIC CALORIMETERS EMPLOYING UNDEPLETED SILICON DETECTORS

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Abstract

The application of silicon detectors in electromagnetic calorimetry has only recently begun, following the development of large area detectors of low resistivity which can successfully operate undepleted (not fully depleted).

This paper describes investigations of longitudinal electromagnetic shower development in calorimeters employing silicon detectors as active medium. A comparison of calorimeters employing tungsten, uranium and lead is presented. Also a study of the dependence of the energy response of a silicon sampling calorimeter on the depletion depths of the silicon detectors, with tungsten as an absorber, is given.

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1. Introduction

The application of silicon detectors in electromagnetic calorimetry has begun recently [1] – [3], following the development of large area detectors of low resistivity which can successfully operate undepleted (not fully depleted) [4].

New colliding beam machines such as the e^+e^- LEP and SLC and the ep HERA are in different stages of development and construction. Also a high energy $p\bar{p}$ collider SSC has been proposed. For these machines, calorimeters have to possess excellent energy resolution for both electrons and hadron jets. They must also satisfy requirements of compactness and granularity. Sandwich calorimeters are a logical choice for these machines since they satisfy the above mentioned requirements and because they are adequate for the high energies involved in experiments in colliders. The use of silicon detectors as active samplers allows calorimeters to be made both compact and granular.

In an attempt to answer the many questions which arise, from the above calorimeter requirements, the longitudinal shower development of 2, 4, and 6 GeV electrons in a silicon sampling electromagnetic calorimeter was investigated [5], for data taken with both uranium and tungsten absorbers, the silicon detectors being operated with depleted layer widths of both 70 and 200 μm . The mean detected energy with uranium as absorber was found to be about 11% higher than with tungsten. Also the dependence on depletion depth of the energy response of a silicon sampling calorimeter with tungsten absorber was investigated at the CERN – PS with an incoming electron beam of energy 4 GeV [6]. The response of the individual detectors located at depths of 2 to 16 radiation lengths in the calorimeter was found to be a linear dependence of the deposited energy versus the depleted layer width. At depths of 18 to 24 radiation lengths the response was found to be highly nonlinear and showed a rapid growth in deposited energy at large values of depletion depth where the shower contains mainly electrons and photons below the critical energy. However, since the deposited energy in the detectors is small, compared to the overall deposited energy in the calorimeter, it does not affect the linear calorimeter response versus the depleted layer width.

Experimental results are also available from Si/Pb electromagnetic sampling calorimeters. A comparison of the various existing calorimeters for the energy response is presented.

The use of silicon detectors in hadronic calorimetry might allow the investigation of the extent to which the compensation mechanism is related to photons emitted in the fission process (during the development of the hadronic shower) operating the calorimeter at different depletion depths.

2. Silicon sampling calorimeters

2.1 *Properties of sampling calorimeters with undepleted Si detectors*

To achieve the best possible energy resolution, for hadronic showers, a silicon sampling calorimeter should have the same response to pions as to electrons. Therefore, for pions the calorimeter must compensate for energy, lost in nuclear break-up, induced by the strong interaction. Data on longitudinal shower development are lacking and it is not known whether compensation occurs at particular depths in the shower, or whether it depends on the sampling frequency, or signal collection time. Furthermore, a good energy resolution for electromagnetic showers is needed. Thus, the longitudinal shower development, its dependence on the depletion layer width and the energy resolution for electromagnetic showers have been investigated.

2.1.1 Longitudinal shower development and energy resolution

The longitudinal shower development of 2, 4 and 6 GeV electrons (from CERN – PS) in a silicon sampling electromagnetic calorimeter was studied [5] for data taken with both uranium and tungsten absorbers and with silicon detectors operated with depleted layer widths of 70 and 200 μm . The silicon detectors and their associated electronics oriented to calorimetry [4], [7] as well as the electromagnetic calorimeter [8] have been described previously. The calorimeter contained 24 radiation lengths of either uranium or tungsten. Each detector was placed in the calorimeter, so that the junction side faced the beam.

The longitudinal shower development has a two component structure which can be parametrized by [2], [5]:

$$\epsilon = \epsilon_0 (t/2)^2 \exp(-bt) + \epsilon_1 (t/2)^c \exp(-m(t-x_1)-y_1) \text{ [MeV]}$$

where ϵ is the deposited energy as a function of t , t is the depth of the passive material in radiation lengths, ϵ_0 and ϵ_1 are normalization constants proportional to the depleted layer width, a , b , c , m , x_1 and y_1 are dimensionless parameters which vary logarithmically with the number of [GeV]s of the incident energy E :

$$a = a' + a'' \ln E, b = b' + b'' \ln E, c = c'' \ln E, m = m'' \ln E, x_1 = x_1' + x_1'' \ln E.$$

Thus for t less than 14, the shape of the longitudinal shower development does not depend on either the absorber, uranium or tungsten, or the depletion layer width. At depths greater than 18, a second component is present in the shower decay. This component depends on both the absorber type and silicon detector depletion width.

In fig.1 the energy response of the calorimeter as a function of the incoming electron energy is presented. The mean detected energy with uranium as absorber is about 11% higher than with tungsten.

The energy resolution, for sensitive depths of 200 [2] and 1000 μm [1] and fully contained electromagnetic showers is

$$\sigma(E)/E \approx 17\% (\sqrt{\tau}/E)$$

where E is the incoming electron energy in GeV and τ is the sampling frequency.

The energy resolution is degraded by no more than 10 – 15% by employing detectors operated with depleted layer width of 70 μm [5].

2.1.2 Energy response dependence on the depletion depths

The dependence of the energy response of a silicon sampling calorimeter on the depletion depths of the silicon detectors has been investigated with tungsten as an absorber and an incoming electron beam with an energy of 4 GeV [6]. The calorimeter contained 24 radiation lengths of tungsten, with a silicon detector located after each two radiation lengths of absorber. The beam and calorimeter config-

urations have been previously reported [2] and both 200 and 70 μm depletion depth results presented. The response of the individual detectors located at depth of 2 to 16 radiation lengths in the calorimeter was found to be a linear dependence of the deposited energy versus the depleted layer width. The response of detectors located at depths of 18 to 24 radiation lengths (fig.2) is highly nonlinear and shows a rapid growth in deposited energy at large values of depletion depth where the shower contains mainly electrons and photons below the critical energy. However, since the deposited energy in these detectors is small compared to the overall deposited energy in the calorimeter, it does not affect the linear calorimeter response versus the depleted layer width.

2.2 Comparison of Si sampling calorimeters

In addition to the CERN electromagnetic sampling calorimeters, consisting of sandwiches of Si/W and Si/U [5], there are the Tokyo [1] and Hamburg [3] calorimeters made of Si/Pb. Although they are all using silicon as the active medium, they have different effective radiation lengths, critical energies, densities, sampling frequencies and depletion depths [9].

In order to find a well defined procedure for comparison, Rossi's Approximation B [10] was used. For shower development, Rossi's Approximation B assumes: (a) asymptotic values of cross-sections for pair production and bremsstrahlung, (b) constant ionization loss ϵ_{crit} per radiation length for electrons and positrons and (c) zero opening angles in collision processes, (d) no Compton scattering etc. Then, the total track length, T , is given by

$$T = EX_0/\epsilon_{\text{crit}} \quad (1)$$

where X_0 is the radiation length.

In a sampling calorimeter the critical energy and the radiation length are to be replaced by the effective critical energy ϵ_{eff} and the effective radiation length X_{eff} . Thus, the energy sensed by the active silicon planes is

$$E_{\text{Si}} = P_{\text{Si}} T(\epsilon_{\text{Si}}/X_{\text{Si}}) \quad (2)$$

where p_{Si} is the fraction (by mass) of silicon and X_{eff} is the effective radiation length of the calorimeter. From eq(2), η , the ratio of the sensed energy E_{Si} to the incoming energy E

$$\eta = p_{Si}[(\epsilon_{Si}/X_{Si})/(\epsilon_{eff}/X_{eff})] \quad (3)$$

where

$$\epsilon_{eff}/X_{eff} = \sum_i p_i(\epsilon_i/X_i)$$

To calculate the critical energies of the various materials of the calorimeters, the results of the fit of Dovzhenko and Pomanski [11] were used. They give

$$\epsilon_{crit} = B(ZX_0/A)^d \quad [\text{MeV}] \quad (4)$$

where Z is the atomic number of the material, X_0 is the radiation length in g/cm^2 , A is the atomic mass, $B = 2.66$ and $d = 1.11$.

Both the Hamburg and the Tokyo calorimeters were run with the silicon detectors fully depleted while the CERN calorimeters with thickness of $295 \mu\text{m}$ were depleted to 200 and $70 \mu\text{m}$. Because of charge diffusion in the field-free region (the migration effect), the energy response of the calorimeter is greater by an amount corresponding to about $23 \mu\text{m}$ increased depletion depth [12]. Accordingly, effective active layers of 223 and $93 \mu\text{m}$ were taken for the comparison.

The predicted ratio η and the measured η_m are shown in Table 1 [13].

It is expected that the calorimeters see less than predicted, since Approximation B overestimates the track length.

The Tokyo and CERN calorimeters, for which p_{Si} varies by more than one order of magnitude, detect about 70% and 80% of the predicted energy respectively.

The Hamburg calorimeter sees about 43% of the predicted value. This low value is partially explained by lateral and longitudinal losses, both of which are about 10% of the incoming electron energy.

It can be concluded that the data from the Tokyo and CERN calorimeters (which provide both lateral and longitudinal shower containment) are in good agreement. The data from the Hamburg calorimeter cannot be easily compared, since there is no full shower containment.

3. Conclusions

The silicon sampling calorimeter has the potential feature of high stability which allows absolute energy calibration of better than 1%. It is compact, fast, granular and it is not affected by high magnetic field.

It was found that the structure of the longitudinal shower development has two components. One component is in the region of less than 14 radiation lengths and does not depend on either the absorber material or the depletion layer width. The other one is in the region of more than 18 radiation lengths and depends on both the absorber and the depletion width.

The energy resolution was found to be comparable with that achieved with sampling calorimeters like those using liquid argon as active samplers.

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TABLE 1
Calorimeter parameters (comparative)

Group	Sampling type	Phys. thickness (μm)	Active layer (μm)	Active area (cm^2)	Absorber (mm)	$L^{(1)}$	n (%)	η_m (%)	η_m/η (%)	e^- Energies (GeV)
SICAPO	Si/W	295	223	25	7 (2)	24	0.58	0.46	80	2, 4, 6
	Si/W	295	93	25	7 (2)	24	0.25	0.19	77	2, 4, 6
	Si/U	295	223	25	6.3	24	0.67	0.52	78	2, 4, 6
	Si/U	295	93	25	6.3	24	0.28	0.22	78	2, 4, 6
TOKYO	Si/Pb	1000	1000	38	5	10	5.71	3.86 (3)	68 (3)	0.25, 0.375, 0.50, 0.625, 0.75
	Si/Pb	190	190	8	5	12	1.017	0.44	43	1.5, 3.0, 5.0

(1) Calorimeter depth (in radiation lengths).

(2) 97% of tungsten and 3% of Fe and Ni.

(3) includes only first 3 energies.

Figure captions

Fig 1 : Mean energy detected by the calorimeter vs the incoming electron energy for uranium with a silicon depletion layer of 200 μm (■); for uranium with a silicon depletion layer of 70 μm (▣); for tungsten with a silicon depletion layer of 200 μm (●); for tungsten with a silicon depletion layer of 70 μm (○). The full lines are the least squares fits to the data.

Fig 2 : The longitudinal shower development in the silicon/tungsten sampling calorimeter for the depletion depths of $X_D = 40, 70, 100, 125, 150,$ and $200 \mu\text{m}$. The curves superimposed on the data show the results of a linearized least squares fit.

FIG. 1

FIG. 2